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# AN ASSESSMENT OF BINARY METALLIC GLASSES: CORRELATIONS BETWEEN STRUCTURE, GLASS FORMING ABILITY AND STABILITY (PREPRINT)

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**Metals Branch**
**Metals, Ceramics and NDE Division**

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# An assessment of binary metallic glasses: Correlations between structure, glass forming ability and stability

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## Abstract

The objective of this work is to explore the influence of the atomic structure of binary metallic glasses on glass-forming ability and thermal stability. A broad assessment of binary metallic glasses is given, with information on 619 distinct binary alloys from 162 binary glass systems. For each of these glasses, the structure is quantified with the efficient cluster-packing (ECP) model, using reported glass constitutions as input. The glass transition temperatures $T_g$, crystallization temperatures $T_x$, and liquidus temperatures $T_\ell$ are taken from the literature to compute the thermal stability parameters $T_{rg} = T_g/T_\ell$, $T_x/T_\ell$, $\Delta T_x = T_x - T_g$ and $\gamma = T_x/(T_g + T_\ell)$. Comparison of the atomic structures with reported amorphous thickness and thermal stability parameters gives the following major results. Binary glasses show a strong preference for solute-to-solvent atomic radius ratios, $R$, that produce efficient local atomic packing, consistent with earlier results. Of the thirteen $R$ values that provide efficient local atomic packing in metallic glasses, only five are commonly reported. Minimum and maximum solute atom fractions, $F_\alpha$, are predicted as a function of $R$ from structural considerations, including the minimum needed to fill cluster-forming $\alpha$ solute sites and the maximum based on an iso-structural condition. With only one exception, all of the binary glass alloys fall within these bounds, which cover a broad range of compositions and relative atom sizes. A more limited range of structural topologies is displayed by the most stable binary metallic glasses. These include glasses with $\Delta T_x > 20$ K and

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the binary bulk metallic glasses (BMGs), with unusual glass-forming ability and a reported thickness of at least 1 mm, found in the Ca-Al, Cu-Hf, Cu-Zr, Hf-Cu, Ni-Nb and Zr-Cu systems. These glasses have $R$ values near 0.710, 0.799, 1.116 or 1.248 that produce structure-forming solute-centered clusters with <9>, <10>, <15> and <17> solvent atom sites as nearest neighbors, respectively. The most stable binary glasses are also always solute-rich, representing solute atom fractions that depend on $R$ and range from $0.33 \le F_\alpha \le 0.64$ for $R = 0.617$ to $0.17 \le F_\alpha \le 0.39$ for $R = 1.433$. This provides enough solute atoms, α, to fill all of the α, β and γ solute sites and roughly 1/3 of the Ω (solvent) sites in the ECP structural model. This suggests that $\alpha_\Omega$ anti-site defects, where α solutes occupy Ω sites, are important in the glass-forming ability of the most stable glasses. This stabilizing effect results from an increase in the number of more stable α–Ω bonds, and by producing topologies that enable efficient global atomic packing. A major conclusion of this study is that the best metallic glasses satisfy both the $R$ and solute-rich criteria simultaneously, providing a useful predictive tool for the exploration and discovery of new binary BMGs. The most stable metallic glasses also have absolute differences in solvent and solute bulk moduli $|B_\Omega - B_\alpha|$ less than 60 GPa, and have absolute differences in solvent and solute Pauling electronegativities $|\chi_\Omega - \chi_\alpha|$ equal to ~0.3 or ~0.6. The structural parameters studied here show no systematic influence on the thermal stability parameters $T_{rg}$, $T_x/T_\ell$, $\Delta T_x$ or $\gamma$.

*Keywords*: metallic glass, atomic structure, topology, stability

## 1. Introduction

It has long been suggested that metallic glass stability and glass-forming ability (GFA) are influenced by atomic structure, but it has been difficult to systematically explore this idea until recently. The efficient cluster packing (ECP) model gives a simple approach to specify and characterize metallic glass structures [1, 2]. From this model, metallic glass structures can be constructed from topology alone (the relative sizes and numbers of constituent atoms). The ECP model shows that metallic glass structures are comprised of a solvent atom and one to three solute species of different sizes which are taken from 11 available atomic sizes that give efficient local atomic packing. Considering the distinct number of ways that the different structural sites can be filled by the available atom sizes, and from the type of defect states that can exist, 276 topologically unique atomic structures have been outlined for metallic glasses [2]. Aside from the expectation that structures with higher global packing efficiency may give more stable glasses, there is no fundamental basis for predicting stability from topology alone. It is thus not known if some of these 276 structures are intrinsically more stable than others, or if all provide a roughly equal topological contribution to metallic glass stability.

Using an ECP analysis, the structural topology can be obtained from the alloy specification, which gives the constituent atom species (and hence atomic sizes) and their concentrations. As the alloy specification is given for essentially every glass reported in the literature, and since many thousands of distinct metallic glasses have been produced and reported in the past 48 years, an enormous amount of information is available from which structural topology can be assessed. The critical cooling rate needed to produce a fully amorphous product is a principal metric of GFA, but it is difficult to measure and is rarely reported. A more practical measure of GFA is the maximum amorphous thickness that can be produced, and this information can be taken from the literature to establish correlations between structural topology and GFA. Thermal stability can be represented by primary parameters such as glass transition temperature ($T_g$) and crystallization temperature ($T_x$), and by derived quantities such as reduced glass transition temperature ($T_{rg}$ =

$T_g/T_\ell$, where $T_\ell$ is the liquidus temperature), $T_x/T_\ell$, the temperature interval $\Delta T_x = T_x - T_g$, and $\gamma = T_x/(T_g + T_\ell)$ [3].

The goal of this assessment is to explore the influence of metallic glass structure and topology on GFA and thermal stability. To bound the problem to a workable subset and to simplify structural determination, the present work considers only binary metallic glasses. The data needed to explore correlations between atomic structure, GFA and metallic glass stability are collected from the literature. The ECP model is used to define the structural topology and defect state for each metallic glass in this assessment. Analysis of the topological characteristics and glass stability are conducted to identify relationships between these quantities. These relationships are used to develop more quantitative insights into the role of structure on the GFA and stability of metallic glasses.

## 2. Approach

### *2.1 Data collection*

An extensive review of the literature was conducted to collect the data needed for binary metallic glasses. Only metallic glasses produced by quenching from the liquid are considered. Amorphous solids produced by techniques such as mechanical alloying, electro-deposition and vapor deposition are not included. Data retrieved from the literature include alloy specification, amorphous thickness and representative temperatures $T_g$, $T_x$, $T_\ell$. The compositions used in the present review are usually nominal compositions given by the pre-melting weight of the elements– measured compositions are rarely reported. Measured weight loss is sometimes given, and this data supports reporting compositions to 2 or 3 significant digits. Minority species picked up during processing may be present and may influence results, but such information is rarely available. Liquidus temperatures were taken from binary phase diagrams [4] where this value was not provided in the cited papers. Common thermal stability parameters derived from $T_g$, $T_x$ and $T_\ell$ were calculated, including $T_{rg}$, $T_x/T_\ell$, $\Delta T_x$ and $\gamma$. Atomic radii used here are based on a recent assessment [2], on published values [5-8] and on measured interatomic separations in

metallic glasses, and are given in Table 1. The radii of several elements have been modified slightly from earlier assessments (see Section 4.8). The assessed precision is ±6 pm. The elastic properties of the constituent elements are taken from [8] to explore the suggestion that this property may influence GFA [9], and Pauling electronegativities are taken from [8] to explore a possible correlation with GFA. Where available, additional structure-specific data such as density and partial coordination numbers are also tabulated from the cited literature. The collected data and the citations are compiled in Table A1 of the Appendix.

*2.2 Structural assessment*

The solvent (Ω) and solute (α) species produce structure-forming clusters that consist of a central α site surrounded by Ω sites. These clusters are centered at positions in space that approximate to a cubic close-packed (ccp) lattice. Additional solute sites are formed in the structure, including β sites that are surrounded by an octahedron of these clusters and γ sites surrounded by a tetrahedron of clusters. In binary glasses, there are thus two species *i* (solvent atoms Ω and solute atoms α) and four sites *j* (Ω, α, β and γ). The number of structural sites can be counted in the ECP model, where $\hat{S}_j$ is the total number of *j* sites per α site [1, 2]. By definition, $\hat{S}_\alpha = 1$. From ccp symmetry, there is 1 β site and 2 γ sites for every α site, so that $\hat{S}_\beta = 1$ and $\hat{S}_\gamma = 2$. Each α site in the structure creates $\hat{S}_\Omega$ Ω sites. The value of $\hat{S}_\Omega$ is given by the geometry of efficient local atomic packing around α sites, and depends only on the ratio $R = r_\alpha / r_\Omega$ between the solute radius, $r_\alpha$, and solvent radius, $r_\Omega$, as shown by equation 5 in [10]. The total number of structural sites is $\sum S = \sum_j \hat{S}_j = \hat{S}_\Omega + 4$ [2]. These relationships are illustrated in Table 2.

Metallic glass structures are specified by the way in which the sites are occupied. For binary alloys, eight structural site occupancies, $S(i_j)$, give the number of *j* sites that are occupied by *i* species, normalized by the number of α sites in the structure (Table 2). Quantitative comparisons with structure-specific measurements [2] give no support for a structurally significant presence of solvent anti-site defects on solute sites, so that $S(\Omega_\alpha) = S(\Omega_\beta) = S(\Omega_\gamma) = 0$. The total number of Ω

atoms per α site in the structure, $\bar{S}_\Omega$, is thus given by $S(\Omega_\Omega)$ (see Table 2). The $S(\alpha_j)$ values can be obtained from the metallic glass constitution by determining the total number of α atoms in the structure normalized by the number of α sites, $\bar{S}_\alpha$. The atom fractions are given by

$$F_\alpha = \bar{S}_\alpha / \left( \bar{S}_\alpha + \bar{S}_\Omega \right) \quad 1a$$

$$F_\Omega = \bar{S}_\Omega / \left( \bar{S}_\alpha + \bar{S}_\Omega \right) \quad 1b$$

so that

$$F_\alpha / F_\Omega = \bar{S}_\alpha / \bar{S}_\Omega \quad 2$$

where $F_i$ is the atom fraction of species $i$ and $\bar{S}_i$ is the total number of $i$ atoms in the structure normalized by the number of α sites. As a basic identity from the discussion above, and assuming that all Ω sites are occupied

$$\hat{S}_\Omega = S(\Omega_\Omega) + S(\alpha_\Omega) \quad 3$$

Substituting $\bar{S}_\Omega = S(\Omega_\Omega)$ from above gives

$$\hat{S}_\Omega = \bar{S}_\Omega + S(\alpha_\Omega) \quad 4$$

Rearranging terms and combining with Equation 2 gives the general result

$$\bar{S}_\alpha = \left( F_\alpha / F_\Omega \right) \left( \bar{S}_\Omega - S(\alpha_\Omega) \right) \quad 5$$

that depends only on metallic glass constitution (through the terms $F_\alpha$ and $F_\Omega$), on geometry (through the term $\hat{S}_\Omega$) and on the number of α atoms that occupy Ω sites. Specific solutions are developed below for Equation 5 in solute-lean and solute-rich glasses.

In solute-lean glasses, the number of solute atoms is less than or equal to the number of solute sites, so that $\bar{S}_\alpha \le 4$. Since α atoms fill solute sites before Ω sites [2], there are no solute anti-site defects on Ω sites in solute-lean glasses, and $S(\alpha_\Omega) = 0$. Inserting this in Equation 5 gives the final result for solute-lean glasses

$$\bar{S}_\alpha = \left( F_\alpha / F_\Omega \right) \left( \bar{S}_\Omega \right) \quad 6$$

An important number of solute sites will be vacant when $\bar{S}_\alpha < 4$, so that $S(\alpha_\alpha)$, $S(\alpha_\beta)$and $S(\alpha_\gamma)$ may be less than the maximum values. Solute-rich glasses have all solute sites occupied by α and enough extra to occupy some Ω sites, forming $\alpha_\Omega$ anti-site defects. Since there are four solute sites per α site

$$\bar{S}_\alpha = S(\alpha_\Omega) + 4 \quad (7)$$

Rearranging terms and substituting in Equation 5 gives

$$\bar{S}_\alpha = \left(F_\alpha / F_\Omega\right)\left(S_\Omega - \bar{S}_\alpha + 4\right) \quad (8)$$

Collecting $\bar{S}_\alpha$ terms and simplifying gives the final result for solute-rich glasses

$$\bar{S}_\alpha = \left(F_\alpha\right)\left(S_\Omega + 4\right) \quad (9)$$

$\bar{S}_\alpha$ is thus given by Equation 6 if $\left(F_\alpha / F_\Omega\right)\left(S_\Omega\right) \leq 4$, otherwise it is given by Equation 9. $S(\alpha_j)$ values are determined from $\bar{S}_\alpha$ by filling α solute sites first (to the maximum value of $S(\alpha_\alpha) = 1$), then β sites (to the maximum value of $S(\alpha_\beta) = 1$) then γ (to the maximum value of $S(\alpha_\gamma) = 2$) and finally Ω sites, until $S(\alpha_\alpha) + S(\alpha_\beta) + S(\alpha_\gamma) + S(\alpha_\Omega) = \bar{S}_\alpha$ and the solutes are all accounted for. $S(\Omega_\Omega)$ is determined from Equation 3 once $S(\alpha_\Omega)$ is known.

Normally, solute and solvent elements are taken to be the minority and majority species, respectively. However, this definition becomes ambiguous near the equiatomic composition, especially when the solute and solvent species are different sizes. For example, when $R = 0.80$, each α site is at the center of an efficiently-packed cluster with 10 Ω atoms in the first coordination shell, so that each α site in the structure produces 10 Ω sites. When all of the α sites are filled by α, $F_\alpha = 1/11 = 0.091$; when all of the α and β sites are filled by α the solute atom fraction is $F_\alpha = 2/12 = 0.167$; and when all of the α, β and γ sites are filled by α the solute atom fraction is $F_\alpha = 4/14 = 0.286$. This structure represents many transition metal-metalloid binary glasses such as Co-P and Pd-Si, and also metal-metal glasses such as Zr-Cu and Zr-Ni. Now consider a glass where α is larger than Ω. For example, $R = 1.25$ in Al-Y and Cu-Zr glasses, where each α site now produces 17 Ω sites. In this glass, all of the α sites are occupied when $F_\alpha = 1/18 = 0.056$; all of the α and β sites are occupied when $F_\alpha = 2/19 = 0.105$; and all of the α, β and γ sites are occupied when $F_\alpha = 4/21 = 0.190$. From a structural perspective, larger solutes are thus more potent, since they produce more Ω sites than do smaller solutes.

If we continue to add Cu solutes to the Zr-Cu glasses described above, and we continue to add Zr solutes to the Cu-Zr glasses, we can imagine that an iso-structural condition will eventually be produced. We define the iso-structural condition as the singular structure where the

same structural description is obtained regardless of which atom is used as the solute and which is the solvent. This will occur at the equi-atomic composition when the two atoms are the same size, but it will occur at a different composition in structures with non-equal spheres, since different sized atoms have different structural potency.

The concept of inverse structures is introduced here to give a rigorous, structure-specific definition for solvent and solute species in binary structures with different atom sizes. Consider a glass with solute and solvent radii $r_\alpha$ and $r_\Omega$. $\hat{S}_\Omega$ and other structural parameters are defined using $R = r_\alpha / r_\Omega$ and atom fractions $F_\alpha$ and $F_\Omega$ as described earlier. An inverse structure can also be described for the same glass, using $R^I = r_\Omega / r_\alpha$, $F_\alpha^I = F_\Omega$ and $F_\Omega^I = F_\alpha$. In this way, the solute of a normal structure is the solvent in the inverse structure. The iso-structural condition is defined when the total number of solute atoms per solute site in the normal structure equals the total number of solute atoms per solute site in the inverse structure, $\bar{S}_\alpha = \bar{S}_\alpha^I$. This always occurs for solute-rich glasses, so using Equation 9 and the relation $F_\alpha^I = F_\Omega = 1 - F_\alpha$ gives

$$F_\alpha \left( \hat{S}_\Omega + 4 \right) = \left( 1 - F_\alpha \right) \left( \hat{S}_\Omega^I + 4 \right) \qquad 10$$

Rearranging terms gives the α atom fraction at which the iso-structural condition is met

$$F_\alpha^{iso} = \frac{\hat{S}_\Omega^I + 4}{\hat{S}_\Omega + \hat{S}_\Omega^I + 8} \qquad 11$$

From Equation 11, $F_\alpha^{iso} = 0.5$ only when $\hat{S}_\Omega = \hat{S}_\Omega^I$, and this occurs only when $R = R^I = 1$. When $R < 1$, $\hat{S}_\Omega < \hat{S}_\Omega^I$ and $F_\alpha^{iso} > 0.5$, and when $R > 1$, then $\hat{S}_\Omega > \hat{S}_\Omega^I$ and $F_\alpha^{iso} < 0.5$. In the present analysis, structural parameters are determined for both cases: when the α constituent is taken as the smaller atomic species ($R$<1) and when the α constituent is taken as the larger atomic species ($R$>1). The solute is defined as the species that gives the smaller value of $\bar{S}_\alpha$. Throughout this work, the terms α and Ω are used to represent the solute and solvent species, respectively, as established by this criterion.

An adjustment is made in $\hat{S}_\Omega$ to account for a change in the number of structural sites that accompanies a significant number of $\alpha_\Omega$ defects in solute-rich glasses. An effective solvent radius is given as

$$\tilde{r}_\Omega = r_\Omega \left( \zeta(\Omega_\Omega) / \hat{S}_\Omega \right) + r_\alpha \left( \zeta(\alpha_\Omega) / \hat{S}_\Omega \right) \quad 12$$

where $r_i$ is the atom radius. Since $\hat{S}_\Omega$ depends on the effective solvent size, Equation 12 is solved iteratively. This correction applies only to solute-rich glasses, or about 40% of the alloys in this study. The average adjustment to $\hat{S}_\Omega$ is less than 5%, and is never more than 15%. Throughout this work, the term $\hat{S}_\Omega$ is understood to incorporate this correction.

This structural analysis has been applied to all of the binary metallic glass alloys in this assessment. The glass constitutions are given as solute and solvent species and solute atom fractions, $F_\alpha$. The structural parameters include the nominal radius ratio $R$, the effective radius ratio $\tilde{R} = r_\alpha / \tilde{r}_\Omega$, $\hat{S}_\Omega$, $\bar{S}_\alpha$, $\bar{S}_\Omega$ and $S(i_j)$ values. These data are included in Table A1 of the Appendix.

## 3. Results

The elements found in binary metallic glasses are presented in Section 3.1, followed by the phenomenological correlations between the measured amorphous thickness and the resulting thermal stability parameters (Section 3.2). The remainder of the results is devoted to establishing the influence of atomic structure (Sections 3.3 through 3.5) and physical properties of the constituent elements (Sections 3.6 and 3.7) on the thermal stability and thickness of binary metallic glasses.

### *3.1 Elements found in binary metallic glasses*

A total of 619 distinct metallic glass alloy compositions are identified from 162 different binary systems (Table A1). An A-B glass system is counted separately from the B-A glass system in the present study, since they are topologically distinct and are separated by the iso-structural condition defined by the composition in Equation 11. Forty-one elements are solvents and 49 elements are solutes, representing a total of 56 different elements (Figure 1). Solutes or solvents are taken from alkaline earth metals, early and late transition metals, lanthanides and actinide elements. Other metal elements include Al, Ga, Sn and Pb. Nearly all of the metalloids, including B, Si, Ge, As, Sb and Te, and nearly half of the non-metals, including C, N and P, are

constituents of binary metallic glasses. Binary metallic glasses containing alkali metals, inert gas and halogen elements were not found in this assessment. Most metallic elements have been used to produce binary metallic glasses, and the number of binary glass systems contained in this assessment represents over 5% of the binary systems possible from the 56 elements represented. While metallic glasses are unusual, it is no longer true that they are rare.

*Figure 1 near here.*

*3.2 Influence of thermal parameters on GFA*

While binary glasses generally have poor GFA, sixteen binary bulk metallic glass (BMG) alloys, defined as glasses that can be produced by melt quenching to thicknesses ≥1 mm, are reported in six binary systems (Table A2). With the exception of the Ca-Al BMG, the binary BMGs are pairs of early and late transition metals. These include the inverse glass-forming pairs of Cu-Hf and Hf-Cu, and of Cu-Zr and Zr-Cu. Only single compositions are reported for Ca-Al and Hf-Cu BMGs, but the remaining four BMG systems cover $F_\alpha$ ranges of 0.02 to 0.05. These BMGs allow analysis of relationships between the maximum reported amorphous thickness and thermal stability parameters such as $T_{rg}$, $\Delta T_x$, $T_x/T_\ell$ and $\gamma$. Correlations between thickness and these thermal stability parameters are shown in Figure 2. Binary BMGs require minimum values of approximately 0.55 for $T_{rg}$; 0.59 for $T_x/T_\ell$; 0.38 for $\gamma$; or 10 K for $\Delta T_x$. Once these minimum values are achieved, there seems to be no systematic increase in amorphous thickness with increasing thermal stability.

*Figure 2 near here.*

In addition to relationships between thickness and derived thermal stability parameters, correlations may also exist between thickness and the basic thermal quantities $T_\ell$, $T_x$ and $T_g$. Figure 3 shows the GFA, represented by the reported amorphous thickness, and derived thermal stability parameters plotted against these three basic thermal parameters. A wide range in

temperatures is reported for binary metallic glasses. The most stable glasses tend toward the lower half of the temperature range found for $T_\ell$ (Figure 3a) and the upper half of the temperature range for $T_g$ (Figure 3c). Once again, the small number of relatively stable binary metallic glasses makes an unambiguous determination of these trends difficult.

*Figure 3 near here.*

*3.3 Solute atom fraction and solute-to-solvent radius ratio in binary metallic glasses*

The two principal topological parameters in binary metallic glass structures are the relative size and relative number of Ω and α atoms. These parameters are plotted in Figure 4, where the relative number of atoms is given by the solute atom fraction, $F_\alpha$. The vertical bars indicate a range in reported compositions for a given binary glass system. Radius ratios range from 0.609 to 1.456 (the value $R = 0.443$ for Gd-C is a singular exception that significantly extends the range of $R$ values), and $F_\alpha$ ranges from 0.06 to 0.625. There are essentially no metallic glasses with $R$~1 (Mg-Zr is the sole exception), in agreement with the long-held empirical observation that a radius ratio difference greater than 12% is needed for good GFA [11-15]. The dashed line in Figure 4 indicates the boundary between solute-lean and solute-rich glasses. Binary BMGs are indicated separately by filled symbols, and it is found that all binary BMGs are solute-rich. Structurally, these BMGs have no vacant solute sites and have significant numbers of solute anti-site defects. The solid line indicates the iso-structural composition as a function of $R$, and is the upper limit on $F_\alpha$. With the exception of Ca-Al, binary BMGs tend toward the iso-structural composition. The dotted line represents the values of $F_\alpha$ needed to satisfy the condition $\bar{S}_\alpha = 1$, proposed here as the minimum solute atom fraction needed to form a metallic glass by liquid quenching (see Section 3.5)

*Figure 4 near here.*

A histogram of the relative atomic sizes of Ω and α in binary metallic glass systems is shown in Figure 5. The nominal radius ratio, $R = r_\alpha / r_\Omega$ , from each of the 162 binary glass systems is placed in a bin with an interval between $R$ and $R$+0.02. The vertical bars in this figure give the total number of systems where $R$ falls within the indicated interval. The values from all of the vertical bars in Figure 5 sum to 179, as the Gd-C system occurs at a value of $R$ much lower than the range included in this figure. A clear preference for specific radius ratios is shown, consistent with earlier work [10]. The specific radius ratios, $R^*$, needed to give efficient local atomic packing of $Z$ solvent atoms around a central α solute (Table 3) are indicated by the vertical lines in Figure 5. Metallic glasses most commonly have a radius ratio near $R^*$=0.799, indicating a structure that is comprised of solute-centered atomic clusters with $Z$=10 and designated as a <10> glass [1]. Additional significant peaks are shown at $R^*$=0.710, $R^*$=0.902, $R^*$=1.116 and $R^*$=1.248 representing <9>, <12>, <15> and <17> structures, respectively. Far fewer glasses have radius ratios near $R^*$=0.617, $R^*$=1.311 and $R^*$=1.433. An insignificant number of <6>, <7>, <13>,<14>, <16> and <19> binary metallic glasses have been reported. Four of the 6 binary BMG systems have $R$ near $R^*$=0.799 or $R^*$=1.248, and the remaining 2 have $R$ near 0.710 and 1.116. This dataset suggests that GFA is best for <9>, <10>, <12>, <15> and <17> glasses.

*Figure 5 near here.*

Additional trends are highlighted by replotting the data of Figure 5 to count the number of glasses within an increment $R$+Δ$R$ and an increment $F_\alpha$+Δ$F_\alpha$. The Kriging gridding method [16], commonly used to convert irregularly-spaced data into contour and surface plots, was applied using an interval of 0.05 for both Δ$R$ and Δ$F_\alpha$ with an overlap of 0.025. The integrated number of alloys per specified interval in $R$ and $F_\alpha$ is shown in Figure 6. Glasses with $R \cong 0.799$ that span a composition interval from about $0.16 \le F_\alpha \le 0.24$ are most commonly reported. Glasses with $R \cong 1.25$ are the next most common within the composition range $0.09 \le F_\alpha \le 0.13$. Lesser peaks occur near $R = 0.67$ and $F_\alpha = 0.19$; $R = 0.73$ and $F_\alpha = 0.33$; $R = 0.79$ and $F_\alpha = 0.39$; $R = 0.81$ and $F_\alpha = 0.30$; and $R = 1.25$ and $F_\alpha = 0.37$.

*Figure 6 near here.*

*3.4 Influence of solute-to-solvent radius ratio on GFA and stability*

In the following series of plots, the GFA (represented throughout this work by the maximum reported fully amorphous thickness) and the glass stability (represented by the thermal parameters $T_{rg}$, $T_x/T_\ell$, $\Delta T_x$ and $\gamma$) are compared with metallic glass characteristics, emphasizing glass topology but also including physical characteristics. Figure 7 plots these parameters against $R$. Binary BMGs, where the thickness is ≥1 mm, occur near $R^*$ values that suggest structure-forming clusters with $Z$ of <9>, <10>, <15> and <17>. A strong correlation is also seen for $\Delta T_x$, where the highest reported values occur near $R^* = 0.799$ and $R^* = 1.248$, reinforcing the dominance of <10> and <17> structures. The values of $T_{rg}$ span a range from 0.346 to 0.638, but show neither a strong correlation with specific values of $R$ nor a systematic variation with $R$. The same is true for $T_x/T_\ell$, which ranges from 0.222 to 0.680, and for $\gamma$, which varies from 0.263 to 0.417. Linear regressions for these three parameters all have shallow slopes and correlation coefficients below 0.6. Similar trends are shown for other structural parameters that are explicit functions of $R$, such as the number of structural sites around each α site, $\hat{S}_\Omega$, and the coordination number, $Z$, given by the closest integer to $\hat{S}_\Omega$.

*Figure 7 near here.*

*3.5 Influence of solute atom fraction on GFA and stability*

There is only a weak dependence of $T_{rg}$, $T_x/T_\ell$ and $\gamma$ on $F_\alpha$ (Figure 8). While the slopes obtained by linear regression are slightly larger than for the comparison with $R$ in Figure 7, they are still rather small and the correlation coefficient remains low, so that the natural scatter in the experimental data is likely to overcome the slight systematic variation in these terms with $F_\alpha$. However, there is a strong influence of $F_\alpha$ on the maximum reported thickness and $\Delta T_x$. All binary BMGs are solute-rich, so that the highest values of thickness and $\Delta T_x$ occur for glasses

where $F_\alpha$ is greater than 0.33 (Figures 4, 8). The boundary between solute-rich and solute-lean structures varies significantly with $R$ (Figure 4), and so it is difficult to show the effect of this structural transition in Figure 8.

To illustrate the influence of the solute-lean to solute-rich structural transition, the stability parameters are shown against the number of α atoms per α site in the structure, $\bar{S}_\alpha$ in Figure 9. With $Fe_{91}B_9$ as the only exception, all of the glasses have $\bar{S}_\alpha \geq 1$. Since α atoms fill α sites first, this shows that the α sites are typically fully occupied by α atoms in binary metallic glasses. This validates a major earlier assumption of the ECP model, and underscores the dominant role of α-centered clusters in forming the structural scaffold for metallic glasses. Since there is 1 β site and 2 γ sites for each α site, the α, β and γ solute sites are all filled when $\bar{S}_\alpha = 4$, which defines the boundary between solute-lean structures with solute vacancies and solute-rich glasses with $\alpha_\Omega$ solute anti-site defects. All binary BMGs have $\bar{S}_\alpha > 4$. The number of $\alpha_\Omega$ defects produced when α atoms occupy Ω sites can be obtained by subtracting 4 from $\bar{S}_\alpha$ in Figure 9. Thus, the best binary glasses usually have from 2 to 4 $\alpha_\Omega$ defects per α site. The GFA and stability parameters are plotted against the fraction of Ω sites occupied by α in Figure 10. Solute-lean glasses have a value of $S(\alpha_\Omega)/\hat{S}_\Omega = 0$ in this plot, and the best glasses have roughly between 20-40% of the Ω sites filled by α.

*Figures 8-10 near here.*

*3.6 Influence of* $r_\Omega$, $T_\ell$, *and constituent element elastic properties on GFA and stability*

Topological and thermodynamic modeling of metallic glasses has predicted an increase in $T_{rg}$ with increasing solvent atom radius, $r_\Omega$, and/or solvent shear modulus, $G_\Omega$; with decreasing liquidus temperature, $T_\ell$; with decreasing solute bulk modulus, $B_\alpha$; and with decreasing difference between Ω and α bulk moduli, $|B_\Omega - B_\alpha|$ [9]. In nominal agreement with these predictions, $T_{rg}$ is seen to increase slightly with decreasing $T_\ell$ (Figure 3a), with decreasing $B_\alpha$ (Figure 11) and with decreasing $|B_\Omega - B_\alpha|$ (Figure 12). The magnitude of the change in $T_{rg}$ with

the indicated parameters is small, and linear regression gives a rather small fitting coefficient, from 0.28 to 0.47. Further consideration (Section 4.6) suggests that there is no significant effect of these parameters on $T_{rg}$. There is no apparent influence of $r_\Omega$ (Figure 13) or $G_\Omega$ (Figure 14) on $T_{rg}$. With the exception of $T_\ell$, these parameters show no significant effect on $T_x/T_\ell$ and $\gamma$ (Figures 11-14). Since these two parameters are inversely proportional to $T_\ell$, decreasing $T_\ell$ leads to a slight increase in $T_x/T_\ell$ and $\gamma$, as expected (Figure 3a).

These same physical characteristics exert a range of distinct influences on $\Delta T_x$ and GFA. As in the comparisons of Section 3.4 and Section 3.5, $\Delta T_x$ and GFA both follow the same trends. A clear threshold dependence is shown in Figure 12, where all of the most stable glasses have $|B_\Omega - B_\alpha|$ values less than 60 GPa. Although less clear, a similar trend is suggested for $T_\ell$ (Figure 3a) and $B_\alpha$ (Figure 11), where the most stable binary glasses are found only for the lower half of the ranges in $T_\ell$ and $B_\alpha$ values shown. There seems to be no influence of $r_\Omega$ (Figure 13) and $G_\Omega$ (Figure 14) on $\Delta T_x$ and GFA.

*Figures 11-14 near here.*

*3.7 Influence of electronegativity on GFA and stability*

A comparison is made between electronegativity, $\chi$, of the constituent elements and the GFA and stability. The absolute value of the difference in Pauling electronegativity of the solvent and solute constituents is used here, $|\chi_\Omega - \chi_\alpha|$. Binary glasses with the best GFA have discrete electronegativity differences of either ~0.3 or ~0.6 (Figure 15). These small differences in electronegativity suggest a component of covalent bonding with a slightly polar nature between Ω and α, similar to the bonding in intermetallic systems such as Ni-Al, Co-Al, Mo-Si and Fe-C. The preference shown here for specific differences in electronegativities may be an artifact of the small number of binary BMG systems- only 4 distinct pairs of atom species are found in this assessment. More complicated electronegativity functions were also considered here, including

an averaged electronegativity weighted by the constituent atom fractions [17]. No correlations were found with these other electronegativity functions.

*Figure 15 near here.*

## 4. Discussion

### *4.1 Binary metallic glasses are simple proxies for the more expansive family of metallic glasses*

Binary metallic glasses represent a broad and diverse category of relatively simple metallic glasses. They cover a wide range of elements that include most of the element types in the periodic table. A small number of relatively stable glasses is also found, whether measured by an amorphous thickness of more than 1 mm or by thermal stability parameters. These characteristics qualify binary metallic glasses as a simple proxy for the more expansive field of metallic glasses. As structural complexity is a hallmark of disordered solids, the relative simplicity of binary metallic glass structures and the relative ease of measuring structure-specific properties such as partial pair distribution functions recommend binary metallic glasses for more extensive characterization. There are surprisingly few studies that measure the influence of glass composition on structure-specific properties. The influence of systematic changes in binary composition on density, partial coordination numbers and free volume (via indentation, relaxation or positron annihilation) are expected to significantly clarify structural descriptions. Further insights may be available by coupling new experimental data with the structural analysis techniques developed here. Additional structural studies in binary glasses using techniques such as scanning tunneling microscopy and 3D atom probe are suggested for future work.

### *4.2 Thermal stability parameters give post-mortem correlations with GFA*

The data here support the common view that GFA, as measured by the maximum amorphous thickness, depends upon thermal stability. However, once threshold values are achieved for the thermal stability parameters $T_{rg}$, $T_x/T_\ell$, $\Delta T_x$ and $\gamma$, the data show no further correlation (Figure 2

and Table A2). For example, a binary BMG is produced with a thickness of 2 mm when $T_{rg}$ = 0.556, but increasing $T_{rg}$ to 0.638 does not increase the maximum thickness produced. Further, thicknesses less than 2 mm and as low as <100 μm are also produced over roughly the same range in $T_{rg}$. Reported thicknesses are typically not the maximum thickness possible for values less than about 100 μm in the binary glasses assessed here, and this may contribute to this poor correlation. The majority of literature data come from studies to discover new glass-forming compositions or to measure some property of the metallic glass. Processing techniques such as melt spinning and suction casting are often used, since they enable rapid production and require only a small amount of material. Thermal stability can be evaluated in glasses found in these studies, but significant extra material and effort is needed to define the maximum fully amorphous thickness possible. This extra work involves the systematic variation of process variables such as wheel speed in melt-spinning or mold size in casting. Such efforts are rarely reported for binary glasses. Given the possibility that glasses with a large $\Delta T_x$ may also be binary BMGs, casting studies to establish the maximum fully amorphous thickness of the glasses with large $\Delta T_x$ but small currently reported thicknesses are suggested. Also contributing to the lack of a systematic variation in GFA with thermal stability parameters may be the limited number of relatively stable binary BMGs. A critical evaluation similar to the analysis provided here of more complex metallic glasses, where BMGs are more common, may give additional insight and is suggested for future work.

The data in Figure 3 support the suggestion that the amorphous thickness in binary metallic glasses is maximized when threshold values of $T_\ell$ and $T_g$ are achieved. The temperatures proposed from these figures ($T_\ell < 1500$ K and $T_g > 600$ K) are broadly consistent with the expectation that $T_{rg}$ is maximized for BMGs.

*4.3 Atomic structure gives predictive correlation with GFA: Radius ratios*

Relationships between thermal stability parameters and GFA are satisfying from a scientific standpoint, as they validate insights into the physics underlying glass formation. However, they

lack practical appeal since they do not provide a predictive capability, as the glass must first be produced to generate the thermal stability parameters. However, the results here show clear correlations between GFA and structural parameters. These correlations give an important predictive capability, since the structure can be described from only atom sizes (which are readily available) and concentrations (which can be independently specified). The solute-to-solvent radius ratio, *R*, is one of single best structural parameters to predict the occurrence, GFA and thermal stability of binary metallic glasses. Of the 15 specific radius ratios necessary for efficient local atomic packing, only 5 are commonly observed in metallic glasses, and only 4 produce the most stable glasses. Metallic glasses with *R* required for <9>, <10>, <12>, <15> and <17> structures are commonly reported; <8>, <18> and <20> structures are uncommon; and <6>, <7>, <13>, <14>, <16> and <19> structures are rare or not reported (Table 3). The best GFA is achieved for <9> structures with *R*~0.710, for <10> structures with *R*~0.799, for <15> structures with *R*~1.116 and for <17> structures with *R*~1.248. Essentially no <13> or <14> glasses were found in this assessment, confirming the empirical rule that a significant size difference is needed between solute and solvent species to form metallic glasses. A more mechanistic understanding is given by the elastic strain [12] or strain energy [18] needed to destabilize competing crystalline structures. The rarity of <6>, <7>, <16> and <19> glasses is surprising, and there is no explanation at present for this observation.

*4.4 Atomic structure gives predictive correlation with GFA: Atom fraction*

The structural perspective developed here gives minimum and maximum values of $F_\alpha$ required for metallic glasses (Figure 4). With only one exception, all of the 619 binary metallic glasses fall within these bounds. While the bounds on $F_\alpha$ substantiate this structural perspective, it does not provide a compelling aid in the exploration and development of metallic glasses, as a wide range of compositions are included. However, the observation that all of the most stable binary metallic glasses are solute-rich and generally approach the iso-structural condition is a major insight that gives a useful predictive tool for the development of BMGs. This finding has

direct structural implications that include the suggestion that metallic glass stability is diminished by solvent anti-site defects on solute sites, $\Omega_{solute}$, and by solute vacancies, $V_{solute}$. $\Omega_{solute}$ defects are expected to dominate in solvent-rich glasses, where there are insufficient solute atoms to fill solute sites. The data in Figures 4 and 9 show that metallic glasses are formed only when $F_\alpha$ is sufficient to fill at least all the α sites. While it is possible that these same compositions could be produced by structures where solute sites are filled both by α and by Ω, thus producing $\Omega_{solute}$ defects, there is no data supporting the presence of $\Omega_{solute}$ defects. Further, these defects would produce inefficient local atomic packing that is inconsistent with the basic principle of the efficient filling of space that dominates the occurrence of metallic glasses. While $\Omega_{solute}$ defects are not expected to be structurally significant for the reasons discussed here, they may nevertheless occur as thermally-induced defects in small concentrations.

Although metallic glasses are often produced with $V_{solute}$ defects, they do not exist in any binary BMG or in glasses with $\Delta T_x$ larger than 20 K (Figure 9). Qualitatively, the reason that the most stable glasses do not have $V_{solute}$ defects can be understood from the energy penalty (the $P\mathrm{d}V$ term of Gibbs free energy, where $P$ is pressure and $V$ is volume) paid by a condensed solid for free volume– 'free' volume isn't free. Even though vacancy defects in metallic glasses consist of many unoccupied spaces that are small fractions of an atomic volume which are locally distributed about a vacancy site [2], the energy penalty is nevertheless expected to be significant. The free volume provided by vacancies also increases atom mobility, which further degrades the stability of metallic glasses.

In addition to the destabilizing effect of $\Omega_{solute}$ and $V_{solute}$ defects, the preference for solute-rich glasses suggests a stabilizing influence of solutes on β, γ and Ω sites may also exist. β and γ sites are surrounded by Ω atoms from the 1st shells of the bounding α clusters, so that roughly $\hat{S}_\Omega$ new Ω–α bonds are formed for every α atom that occupies a β or γ site ($\beta_\alpha$ and $\gamma_\alpha$ defects). Although the actual magnitudes of atomic bond energies are not known in condensed solids, application of the regular solution model [19] suggests that α–Ω bonds are more stable than the weighted average of α–α and Ω–Ω bonds in metallic glasses, so that solute occupancy of β and γ

sites increases metallic glass stability. A qualitative thermodynamic argument gives a simple basis for the observation shown here that the most stable glasses have roughly between 20-40% of the Ω sites filled by α. Each $\alpha_\Omega$ defect replaces an Ω atom in the 1st shell of an α-centered cluster with an α atom. Considering only bonds within this cluster, removing the Ω atom breaks one α–Ω bond with the central solute atom and 4 or 5 Ω–Ω bonds within the first coordination shell, and placing an α atom on this site forms one α–α bond and 4 or 5 α–Ω bonds. It is quite likely that $\alpha_\Omega$ defects thus give an enthalpic bond energy term that helps stabilize metallic glasses. Considering efficiently-packed clusters with coordination numbers $8 \leq Z \leq 20$ [20], it can be shown empirically that no more than about 1/3 of the Ω sites in the 1st coordination shell can be replaced by α before α–α contacts are introduced in the 1st shell. Beyond this fraction, the number of new α–α contacts increases rapidly and the number of new α–Ω bonds decreases. The finding in this assessment that no more than about 1/3 of the Ω sites are occupied by α (Figure 10) is in broad agreement with this qualitative enthalpic argument. Of course, $\alpha_\Omega$ defects are also likely to give an entropic term that stabilizes solute-rich glasses.

*4.5 Influence of atomic structure on thermal stability*

The linear regression for $T_{rg}$ in Figures 7-9 suggests a weak structural dependence, but this approach gives equal weight to each datapoint regardless of GFA. $T_{rg}$ is clearly seen to be independent of $R$ when only $T_{rg}$ values from binary BMGs are considered, as shown by the regression line in Figure 7. $T_{rg}$ values below this upper bound represent alloys with poorer GFA. The present work shows that all binary BMG structures simultaneously have both a discrete value of $R$ that enables efficient local atomic packing, and a solute-rich composition that fills α, β, and γ sites and roughly 1/3 of the Ω sites. For a glass structure that satisfies the $R$ criterion, poorer GFA and lower $T_{rg}$ values can result when $F_\alpha$ is insufficient for BMG formation. This can be illustrated by data from Zr-Cu glasses (Table A1). Zr-Cu BMGs have $F_{Cu}$ values that range from 0.45 to 0.50 and $T_{rg}$ values that range from 0.552 to 0.585, while Zr-Cu glasses with lower $F_{Cu}$, but the same value of $R$, do not form BMGs and have $T_{rg}$ values that range from 0.496 to

0.542. Chemical considerations may also contribute to poorer GFA and lower $T_{rg}$, as similar $R$ values can be obtained for chemically distinct alloys. The same results extend to the influence of $R$ on $T_x/T_\ell$ and $\gamma$ (Figure 7), and to the impact of solute atom fraction on $T_{rg}$, $T_x/T_\ell$ and $\gamma$ (Figures 8-10). Careful consideration of the data in Figures 7-10 thus shows no influence of structure on $T_{rg}$, $T_x/T_\ell$, or $\gamma$.

Values of $\Delta T_x$ appear to correlate strongly with structure, and seem to follow the same trends as GFA (Figure 3a and Figures 7-15). This apparent difference results from the expanded numerical scale and from the greater degree of variability in $\Delta T_x$ relative to the other stability parameters. Compressing $\Delta T_x$ data to the same vertical scale as for $T_{rg}$, $T_x/T_\ell$ and $\gamma$ shows that the same structural independence is observed for $\Delta T_x$. As mentioned in Section 3.2, the limited $\Delta T_x$ dataset is also an important factor contributing to the lack of a compelling correlation. Critical analysis of the structural influence in more complex glasses is suggested, where many more BMGs exist.

*4.6 Other predictive correlations and interrelationships between GFA and thermal stability*

A weak systematic influence of $B_\alpha$ and $|B_\Omega - B_\alpha|$ on $T_{rg}$ is suggested by Figures 11 and 12. However, applying the approach described in the previous section of considering only $T_{rg}$ values from binary BMGs shows that there is no significant influence. This same data shows a clear partitioning of the most stable glasses– BMGs and glasses with large values of $\Delta T_x$ – to the lowest values of $|B_\Omega - B_\alpha|$. The effect of $|B_\Omega - B_\alpha|$ on GFA and on $\Delta T_x$ (Figure 12) is a new result that validates a prediction from earlier thermodynamic modeling [9]. There is presently no physical basis for explaining the apparent preferred discrete values of $|\chi_\Omega - \chi_\alpha|$ in the most stable binary glasses, and this observation may result from the rather small number of relatively stable binary alloy systems.

The maximum global atomic packing fraction is expected to be a key topological parameter in the stability of metallic glass structures, but there are very few approaches for predicting the packing fraction in binary systems of spheres. Developed for the packing of ceramic particles,

and based on the filling of interstices between larger particles by much smaller particles, the Furnas model [21-23] has been extended empirically to the packing of binary systems of spheres with $R$ ranging from 0.1 to 0.5 [24]. A shallow maximum in the packing fraction is observed in these systems at a volume fraction of smaller particles, $X_f$, of 0.37±0.10. Although the applicability of the concept of smaller spheres filling the interstices of larger spheres diminishes with decreasing difference in size, the efficient packing of larger spheres around a smaller sphere, directed by volume minimization and by chemical interactions, suggests that this approach may give useful insights into atomic packing in metallic glasses. Converting $X_f$ to $F_\alpha$ for glasses with $0.6 \le R \le 0.9$, and truncating $F_\alpha$ at the iso-structure composition, $F_\alpha^{iso}$, the $F_\alpha$ range over which maximal global packing is expected is shown as a function of $R$ by the cross-hatched regions in Figure 4. The predicted solute atom fractions are all solute rich and reach the iso-structural composition. Maximal global packing efficiency can be obtained for glasses with $0.6 \le R \le 0.9$, and the compositions predicted for $R \cong 0.8$ match surprisingly well the actual compositions for binary BMGs with <10> structures. Maximal packing efficiency is also predicted for $0.6 \le R \le 0.9$ when $F_\alpha > F_\alpha^{iso}$, where the inverse structure is the appropriate description of the glass structure. Applying the appropriate conversion for $R$ and $F_\alpha$ (see Section 2.2), the current prediction shows that maximal global packing efficiency can also be achieved for $1.11 \le R \le 1.46$. Reasonable agreement is shown between the predicted and observed values of $R$ and $F_\alpha$ for the binary BMGs with $R > 1$. The trend of achieving maximal global packing efficiency with solute-rich compositions, and the general agreement with selected BMG compositions is encouraging, but additional work is needed to develop more accurate models for predicting global packing efficiency in systems of binary spheres.

The ECP model provides an alternate approach for calculating packing fraction, but density estimates from the ECP model currently have errors as large as 40% [2]. This is insufficient for consideration as a topological criterion. Local topology as given by nearest-neighbor atomic coordination may also provide insights to stability. However, the equations for partial coordination numbers from the ECP model are valid over a restricted composition range that

currently doesn't include solute-rich glasses. Density and partial coordination numbers have direct structural implications, and refinements to the methods by they are calculated within the ECP model are needed to explore these parameters. Measurements of these properties are available in the literature, and have been included in Table A1 for completeness.

The most compelling predictive correlations in this work are shown for the structural parameters $R$ and $\bar{S}_\alpha$ (and the related terms $F_\alpha$ and $S(\alpha_\Omega)/\hat{S}_\Omega$), and for the physical parameters $|B_\Omega - B_\alpha|$ and $|\chi_\Omega - \chi_\alpha|$. It was suggested in Section 4.5 that it may be necessary for both $R$ and $\bar{S}_\alpha$ to be satisfied simultaneously in the most stable binary glasses. Once the $R$ criterion is met, the role of $\bar{S}_\alpha$ can be evaluated, since $F_\alpha$ can be changed while holding $R$ constant, and without changing the chemical bonding between constituent elements. This analysis shows that $\bar{S}_\alpha$ is essential, since the excellent GFA of a binary BMG that satisfies the $R$ criterion becomes dramatically degraded when $F_\alpha$ is reduced below a critical value. It is difficult to determine if $R$ plays the same critical role, since it is not possible to fix $F_\alpha$ and vary $R$ without also changing the constituent elements in the structure, and hence also changing the underlying chemical bonding between elements. However, since global packing efficiency cannot be accomplished without efficient local atomic packing, and since the $R$ criterion provides efficient local atomic packing, then it is concluded that both $R$ and $F_\alpha$ criteria must be met simultaneously to form the most stable metallic glasses. Since all of the most stable glasses in this assessment satisfy all four of the criteria above simultaneously, it is worth considering if all are necessary to form a BMG. It may be that only a subset of these four criteria is sufficient for BMG formation. It is also possible that there are other criteria which cannot yet be established with the data available. The limited number of binary BMGs makes a critical assessment of this issue difficult at present.

*4.7 Inverse glass systems*

Inverse glass systems are companion structures where the solute-to-solvent radius ratio, $R$, and the solvent-to-solute radius ratio, $1/R$, both match values required for efficient local atomic packing. The <10> and <17> structures are inverse systems, since <10> glasses have

$R_{10}^* = 0.799$ and $1/R_{10}^* = 1.252$, which almost exactly match the values $1/R_{17}^* = 0.801$ and $R_{17}^* = 1.248$ for <17> glasses. Only one other pair of structures, <12> glasses with $R_{12}^* = 0.902$ and $1/R_{12}^* = 1.109$ and <15> glasses with $R_{15}^* = 1.116$ and $1/R_{15}^* = 0.896$, match nearly as closely. None of the other structures have a topologically matched inverse system. Thus, the inverse of a <16> glass would have $1/R_{16}^* = 0.845$, which matches neither $R_{10}^* = 0.799$ nor $R_{12}^* = 0.902$ ($R_{11}^*$ glasses are topologically unstable [1, 2]). Satisfying the *R* criterion enables efficient local atomic packing around solute atoms. As $F_\alpha$ increases beyond the iso-structural composition, then the solute species becomes the solvent and vice versa. Since BMGs tend toward the iso-structure composition, and since BMGs are likely to be distinguished as structures with maximal global packing efficiency (Section 4.6), then inverse structures may play an important consideration in BMG stability.

BMGs are obtained for both of the inverse glass systems Zr-Cu and Cu-Zr, as well as for Hf-Cu and Cu-Hf inverse systems. Not only do these represent the companion system pair with the best fit (<10> and <17>), but the actual radius ratios also most closely match the ideal radius ratios needed for efficient local atomic packing. Specifically, the actual *R* values for these four systems (Table A1) vary by less than 0.5% from the ideal $R^*$ values for <10> and <17> structures. Ni-Nb binary BMGs could conceivably have a companion Nb-Ni inverse structure, since $1/R_{15}^* = 0.896$, which is very close to $R_{12}^* = 0.902$. The actual *R* values for these companion glasses (Table A1) deviate from the ideal values $R_{15}^* = 1.116$ and $R_{12}^* = 0.902$ by about 2%, and this may be a factor in the lack of a Nb-Ni binary BMG. Ca-Al glasses are not expected to have a companion inverse glass system, since $1/R_9^* = 1.408$, which is midway between the *R* needed for <19> and <20> glasses. However, the actual *R* for Ca-Al is 0.723, so that *R* for Al-Ca is 1.383 (Table A1). These are within about 1.2% of the ideal *R* values for <9> and <19> glasses. Although Al-Ca glasses exist, they are not reported to be BMGs (Table A1).

Using the binary Zr-Cu alloy system as an example, the relationships between inverse glasses are illustrated in Figure 16. The binary system is divided unambiguously by the iso-structure composition into Zr-Cu glasses and Cu-Zr glasses. The iso-structure composition is bounded by

solute-rich glasses on each side. Cu-rich Zr-Cu BMGs approach the iso-structure composition on one side, while Zr-rich Cu-Zr BMGs approach the iso-structure composition from the other. These two inverse glass systems are structurally distinct– one is a Zr-based glass with a <10> structure, and the other a Cu-based glass with a <17> structure. Only at the iso-structure composition can the glass be described equally well as a Cu-based or a Zr-based glass. The radius ratio criterion is satisfied for these inverse glasses across the full range of $F_\alpha$. Both enthalpic (Section 4.4) and packing fraction (Section 4.6) contributions stabilize solute-rich glasses near the iso-structural composition. The composition of the boundary between solute-lean and solute rich glasses depends on $R$, and varies from $0.25 \le F_\alpha \le 0.33$ for $0.902 \le R \le 0.617$, and from $0.79 \le F_\alpha \le 0.83$ for $1.116 \le R \le 1.433$. As shown in Figure 4, the iso-structure composition varies from 0.53 for $R = 0.902$ to 0.63 for $R = 0.617$. The compositions shown in Figure 16 for the iso-structural composition and for the boundaries between solute-lean and solute-rich glasses are for glasses in the Zr-Cu binary system.

*4.8 Reassessment of atomic radii*

The good alignment of the present radius ratios with $R^*$ values required for efficient local atomic packing improves on earlier results from a more limited dataset [10]. Only binary systems are counted here, rather than distinct alloy compositions, to avoid any bias introduced by more extensive characterization of some systems resulting from practical considerations such as the extent of the glass-forming region, the ease of GFA and the availability of constituent elements. The improved agreement here is achieved in part by a more detailed assessment of atomic radii. The values used here represent a small increase in the radius of B, $r_B$, (from 85 pm to 88 pm) and a decrease in $r_{Ni}$ (from 128 pm to 126 pm) relative to earlier assessments. Previous $r_{Ni}$ values were obtained from pure elements, and $r_B$ was derived by difference from the measured Ni–B separation in $Ni_{81}B_{19}$ [[25]]. These earlier values gave $R = 0.664$, which was too small to give good agreement with the measured coordination number of Ni around B of 9.3. The approach used here acknowledges that atomic radii are slightly smaller for unlike atomic bonding. Thus, a

slightly smaller value of $r_{Ni}$ is used, which gives a slightly larger value of $r_B$ when determined by difference from the same Ni–B separation in $Ni_{81}B_{19}$. The new values used here give $R = 0.698$, in better agreement with the value of 0.710 required for an efficiently packed B-centered cluster with 9 Ni atoms in the first coordination shell. Radii used here for Fe, Rh, Ti, Nb, Au and Hf are reduced by 2 pm each, and $r_{Ta}$ is reduced by 3 pm relative to earlier assessed values. Adjustments were also made to radii for Ba, Ca, Gd, Pt, Nd and Th. All of the modifications in this present assessment are within the stated precision of ±6 pm.

**5. Summary**

Binary glasses are a large and diverse subset of metallic glasses, representing 56 different elements and most element types in the periodic table. Six hundred and thirty seven binary alloys are identified from 162 different binary systems. These 162 binary systems represent over 5% of the possible binary systems that can be produced from the 56 constituent elements, so that binary metallic glasses, although still uncommon, are not rare. Sixteen binary bulk metallic glass (BMG) alloys, being produced in the fully amorphous condition at thicknesses ≥1 mm, are found from 6 systems in this assessment: Ca-Al, Cu-Hf, Cu-Zr, Hf-Cu, Ni-Nb and Zr-Cu. The constitutional breadth, relative structural simplicity and availability of relatively stable alloys recommend binary glasses as convenient proxies for the broader family of more complex metallic glasses.

Metallic glasses are analyzed using the efficient cluster packing (ECP) model, which shows that binary structures consist of 2 species (solvent Ω and solute α) and 4 sites (Ω, α, and additional solute sites β and γ). An approach is developed for evaluating the 8 resulting site occupancy values that define the structural topology, using as input only the relative atomic sizes and atom fractions of the glasses. Other extensions of the ECP model developed here include definition of solute-lean glasses as structures with insufficient α atoms to fill all solute sites, and definition of solute-rich glasses as structures with enough α to fill all available solute sites and to form $\alpha_\Omega$ anti-site defects comprised of solute atoms on Ω sites. A description of inverse

structures is developed, where the solute and solvent species of a normal structure are interchanged. This is used to define the iso-structure condition, which gives an unambiguous structure-based definition of solute and solvent species that is important for solute-rich glasses near the equiatomic composition.

Binary metallic glasses include solute-to-solvent radius ratios from $0.602 \le R \le 1.456$, (the single exception is Gd-C with $R = 0.443$) producing structure-forming, solute-centered clusters with coordination numbers from $7 \le Z \le 20$. Consistent with earlier work, a strong preference is shown for special radius ratios, $R^*$, that give efficient local atomic packing in the 1st coordination shell. This work shows that not all $R^*$ values are equally effective in producing metallic glasses. Binary glasses are most commonly produced with radius ratios near $R^* \cong 0.799$ that give <10> structures, where efficiently packed clusters consisting of a central solute atom surrounded by ~10 solvent atoms form the structural scaffold. Other commonly observed structures include <9>, <12>, <15> and <17> glasses with radius ratios near 0.710, 0.902, 1.116 and 1.248, respectively. Binary glasses are formed less frequently with <8>, <18> and <20> structures, while glasses with $R$ that give <7>, <13>, <14>, <16> and <19> structures are rare or not reported. Thus, only 5 of the 13 radius ratios for metallic glasses are common.

Solute atom fractions in binary metallic glasses range from $0.06 \le F_\alpha \le 0.625$. Rather than using a simple definition of solute species based on atom fraction alone, a structural definition is developed as an explicit function of $R$. Maximum values of $F_\alpha$ increase above 0.5 with decreasing $R$ for $R < 1$ due to decreased structural potency of smaller solute atoms, and maximum values decrease from 0.5 with increasing $R$ for $R > 1$. The minimum $F_\alpha$ values occur when $\alpha$ sites are fully occupied by $\alpha$ solutes, and an explicit structural dependence shows that the minimum $F_\alpha$ values decrease with increasing $R$. With only one exception, all of the 619 binary alloys cited here fall within the compositional bounds derived from these structural considerations. $\alpha$ sites are always occupied in binary glasses, but only by $\alpha$ atoms (the single exception is $Fe_{91}B_9$). $\Omega$ sites are always filled, either by $\Omega$ atoms or by $\alpha$ atoms, forming $\alpha_\Omega$ anti-site defects. $\beta$ and $\gamma$ sites may be vacant or can be filled by $\alpha$, but not by $\Omega$. A significant number

of solute-lean glasses (with vacant β and/or γ sites) and a significant number of solute-rich glasses (with $\alpha_\Omega$ anti-site defects) are shown in this analysis.

The criteria outlined above for $R$ and $F_\alpha$ define the broad topological requirements for glass formation by liquid metal quenching. However, the most stable glasses have outstanding GFA and thermal stability, and satisfy a more restrictive set of conditions. These most stable glasses represent only 4 values of $R^*$, including 0.710 for <9> structures; 0.799 for <10> structures; 1.116 for <15> structures and 1.248 for <17> structures. Further, the most stable glasses are limited to solute-rich compositions that depend on $R$ and range from $F_\alpha > 0.17$ for $R = 1.433$ to $F_\alpha > 0.33$ for $R = 0.617$. From a structural perspective, these glasses all have $\bar{S}_\alpha > 4$ and do not have vacancy defects on either Ω or α sites. Solute sites are all occupied by α, and a significant number of $\alpha_\Omega$ defects occur. The stabilizing influence of $\alpha_\Omega$ defects is suggested to result from a bond enthalpy term, whereby the number of more stable Ω–α bonds in the structure is increased relative to the number of less stable α–α and Ω–Ω bonds. Observed compositions are consistent with a structural argument that predicts that the maximum fraction of Ω sites that can be occupied by α is about 1/3 in the most stable metallic glasses. The $R$ criterion enables efficient *local* atomic packing, while models for maximal *global* packing efficiency suggest that the $R$ and $F_\alpha$ must be met simultaneously. In agreement with this, all of the most stable glasses in this assessment do satisfy both the $R$ and $F_\alpha$ topological constraints simultaneously, representing a significant structural influence on GFA and stability. This finding gives a practically important predictive capability, as the most stable binary metallic glasses are restricted to a relatively narrow range of structural topologies.

In addition to the influence of $R$ and the inter-related quantities $F_\alpha$ and $\bar{S}_\alpha$, the present work also shows an influence of physical characteristics on GFA and thermal stability. The most stable glasses all have an absolute difference in constituent element bulk moduli of $|B_\Omega - B_\alpha|$ <60 GPa. The absolute difference in Pauling electronegativity of Ω and α atoms, $|\chi_\Omega - \chi_\alpha|$, also shows a good correlation with reported amorphous thickness and the thermal stability parameter, $\Delta T_x$. All of the most stable glasses have $|\chi_\Omega - \chi_\alpha|$ equal to either ~0.3 or ~0.6. The thermal stability

parameters Trg, $T_x/T_\ell$, $\Delta T_x$ and $\gamma$ do not show any systematic trends with the topological parameters studied here. Like structure, these relationships provide a predictive capability, as these features can be established before a glass is produced.

Additional work is suggested to solidify and extend the structural insights developed here. Very few studies of binary metallic glasses measure critical thickness, and this information is expected to improve the statistical validity of the correlations explored here. The measurement of structure-specific properties such as density and partial coordination numbers would also enhance structural understanding, especially if carried out in glasses where the constitution and structure are varied systematically. From the structural and analytical foundation provided here, a similar critical assessment of more complex glasses is recommended, where the number of relatively stable BMGs is significantly higher than for binary systems.

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**Table 1. Metallic radii of atoms in metallic glass structures.**

| Element | At # | Radius (pm) | Element | At # | Radius (pm) | Element | At # | Radius (pm) |
|---|---|---|---|---|---|---|---|---|
| **Li** | 3 | 152 | **As** | 33 | 115 | **Eu** | 63 | 196 |
| **Be** | 4 | 112 | **Se** | 34 | 118 | **Gd** | 64 | 174 |
| **B** | 5 | 88 | **Rb** | 37 | 132 | **Tb** | 65 | 180 |
| **C** | 6 | 77 | **Sr** | 38 | 212 | **Dy** | 66 | 175 |
| **N** | 7 | 72 | **Y** | 39 | 179 | **Ho** | 67 | 177 |
| **O** | 8 | 64 | **Zr** | 40 | 158 | **Er** | 68 | 175 |
| **Na** | 11 | 180 | **Nb** | 41 | 143 | **Tm** | 69 | 175 |
| **Mg** | 12 | 160 | **Mo** | 42 | 139 | **Yb** | 70 | 190 |
| **Al** | 13 | 141 | **Tc** | 43 | 136 | **Lu** | 71 | 175 |
| **Si** | 14 | 110 | **Ru** | 44 | 134 | **Hf** | 72 | 158 |
| **P** | 15 | 102 | **Rh** | 45 | 132 | **Ta** | 73 | 145 |
| **S** | 16 | 103 | **Pd** | 46 | 142 | **W** | 74 | 135 |
| **K** | 19 | 230 | **Ag** | 47 | 144 | **Re** | 75 | 137 |
| **Ca** | 20 | 201 | **Cd** | 48 | 157 | **Os** | 76 | 135 |
| **Sc** | 21 | 162 | **In** | 49 | 155 | **Ir** | 77 | 136 |
| **Ti** | 22 | 142 | **Sn** | 50 | 155 | **Pt** | 78 | 139 |
| **V** | 23 | 134 | **Sb** | 51 | 155 | **Au** | 79 | 144 |
| **Cr** | 24 | 130 | **Te** | 52 | 140 | **Hg** | 80 | 152 |
| **Mn** | 25 | 132 | **Cs** | 55 | 264 | **Tl** | 81 | 172 |
| **Fe** | 26 | 125 | **Ba** | 56 | 223 | **Pb** | 82 | 174 |
| **Co** | 27 | 125 | **La** | 57 | 187 | **Bi** | 83 | 162 |
| **Ni** | 28 | 126 | **Ce** | 58 | 182 | **Po** | 84 | 168 |
| **Cu** | 29 | 126 | **Pr** | 59 | 183 | **Th** | 90 | 178 |
| **Zn** | 30 | 138 | **Nd** | 60 | 178 | **Pa** | 91 | 165 |
| **Ga** | 31 | 134 | **Pm** | 61 | 185 | **U** | 92 | 158 |
| **Ge** | 32 | 114 | **Sm** | 62 | 185 | | | |

**Table 2.** **Structural sites and site occupancies $S(i_j)$ per $\alpha$ site.**

| | | Species (*i*) Ω | Species (*i*) α | Site Sum |
|---|---|---|---|---|
| Site (*j*) | Ω | $S(\Omega_\Omega)$ | $S(\alpha_\Omega)$ | $\hat{S}_\Omega$ |
| | α | $S(\Omega_\alpha) = 0$ | $S(\alpha_\alpha) \le 1$ | $\hat{S}_\alpha = 1$ |
| | β | $S(\Omega_\beta) = 0$ | $S(\alpha_\beta) \le 1$ | $\hat{S}_\beta = 1$ |
| | γ | $S(\Omega_\gamma) = 0$ | $S(\alpha_\gamma) \le 2$ | $\hat{S}_\gamma = 2$ |
| **Species Sum** | | $\bar{S}_\Omega = S(\Omega_\Omega)$ | $\bar{S}_\alpha$ | $\sum S = \hat{S}_\Omega + 4$ |

**Table 3.** **Preferred radius ratios, structure and occurrence.**

| R* | <Z> | Occurrence | BMG |
|---|---|---|---|
| 0.414 | <6> | Rare | |
| 0.518 | <7> | None | |
| 0.617 | <8> | Uncommon | |
| 0.710 | <9> | Common | Ca-Al |
| 0.799 | <10> | Common | Hf-Cu, Zr-Cu |
| 0.884 | <11> | Unstable [2] | |
| 0.902 | <12> | Common | |
| 0.976 | <13> | Rare | |
| 1.047 | <14 | None | |
| 1.116 | <15> | Common | Ni-Nb |
| 1.183 | <16> | Rare | |
| 1.248 | <17> | Common | Cu-Hf, Cu-Zr |
| 1.311 | <18> | Uncommon | |
| 1.373 | <19> | None | |
| 1.433 | <20> | Uncommon | |

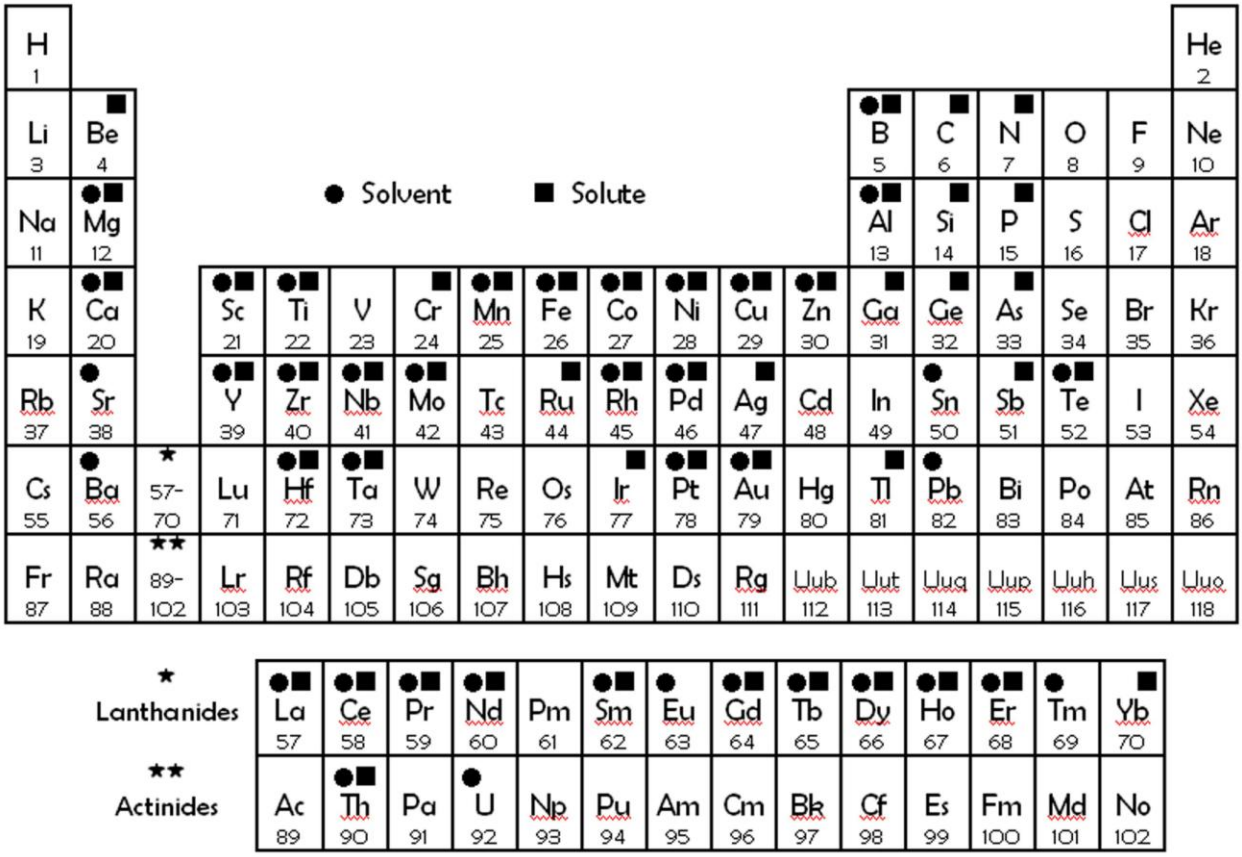



Figure 1 Periodic table showing the solute and solvent atoms found in binary metallic glasses.

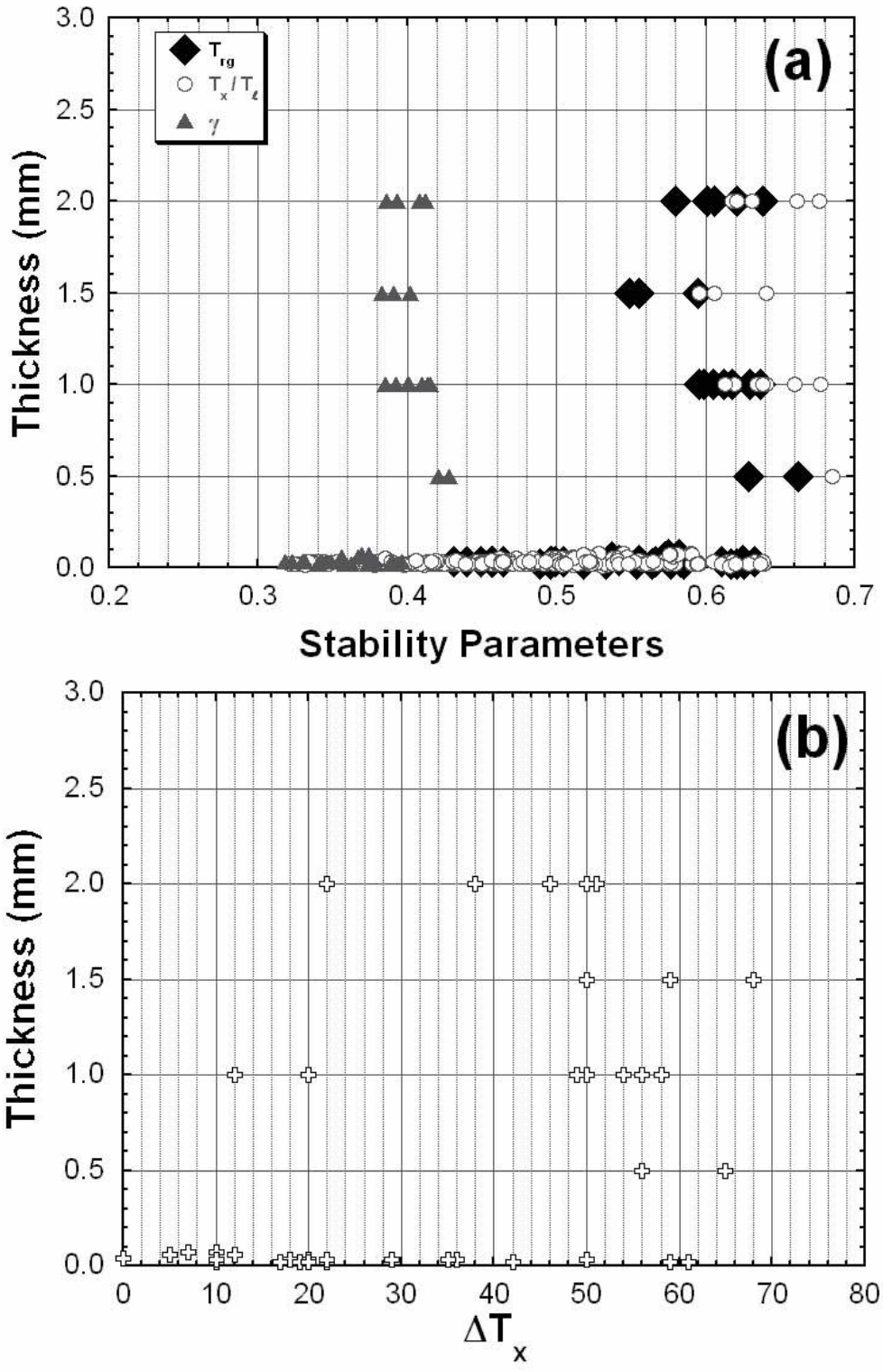
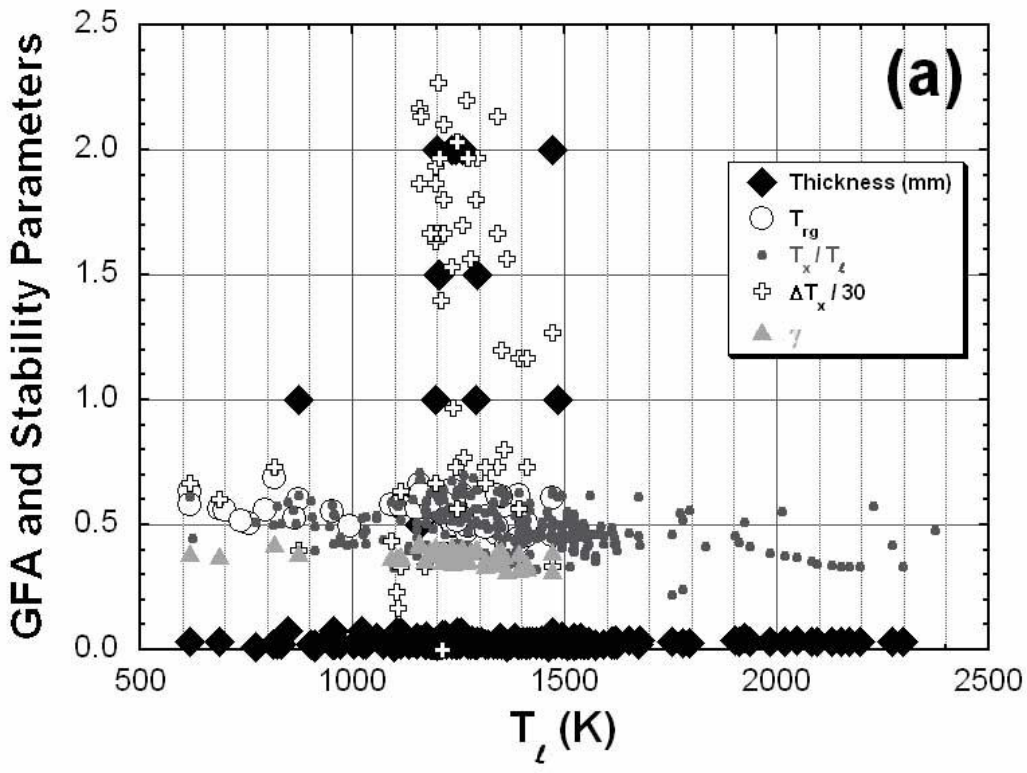
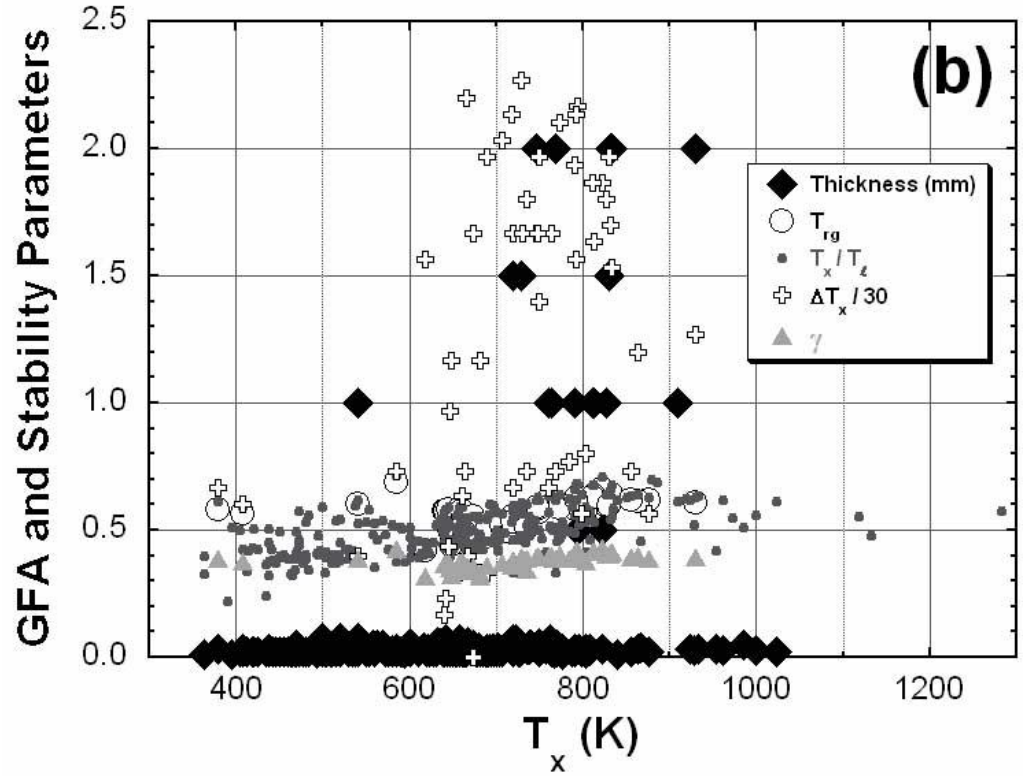



Figure 2 Influence of thermal stability parameters (a) $T_{rg}$, $T_x/T_\ell$ and γ, and (b) $\Delta T_x$ on reported amorphous thickness. Binary BMGs require minimum values of about 0.55 for $T_{rg}$; about 0.59 for $T_x/T_\ell$; 0.38 for γ; or about 10 K for $\Delta T_x$.


(a)
GFA and Stability Parameters
2.5
2.0
1.5
1.0
0.5
0.0
500
1000
1500
2000
2500
$T_\ell$ (K)
Thickness (mm)
$T_{rg}$
$T_x / T_\ell$
$\Delta T_x / 30$
$\gamma$


(b)
GFA and Stability Parameters
2.5
2.0
1.5
1.0
0.5
0.0
400
600
800
1000
1200
$T_x$ (K)
Thickness (mm)
$T_{rg}$
$T_x / T_\ell$
$\Delta T_x / 30$
$\gamma$

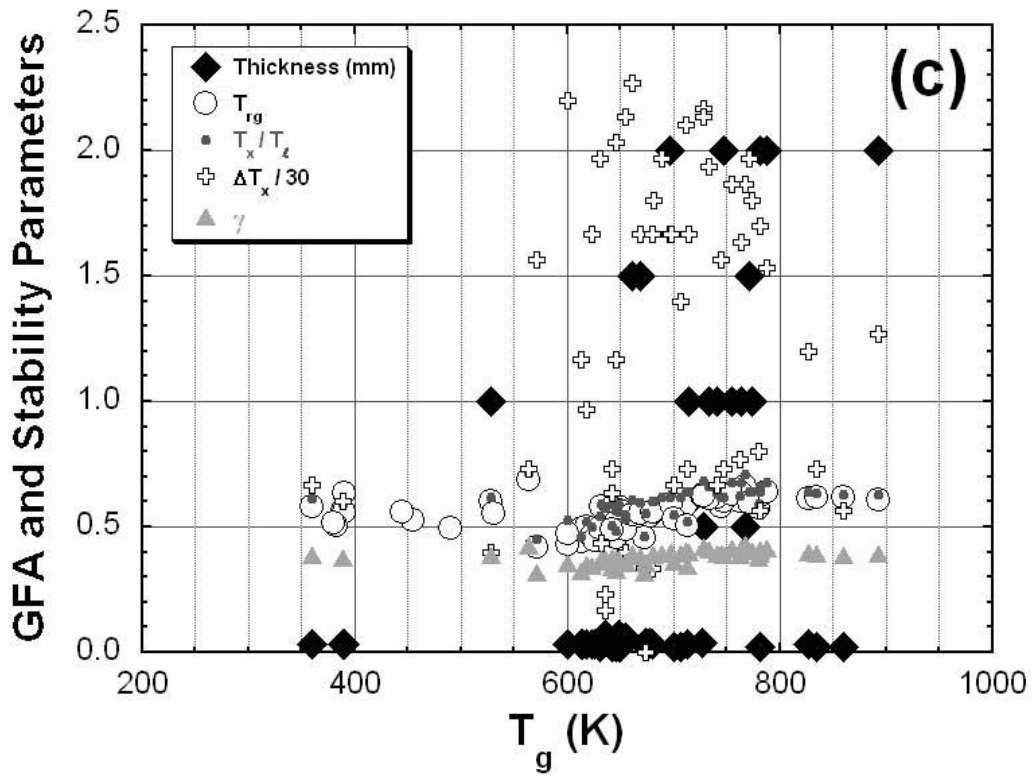



Figure 3 Dependence of the glass forming ability, as measured by the maximum reported amorphous thickness, and derived thermal stability parameters on the primary thermal stability parameters (a) liquidus temperature, $T_l$; (b) crystallization temperature $T_x$; and (c) glass transition temperature, $T_g$. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

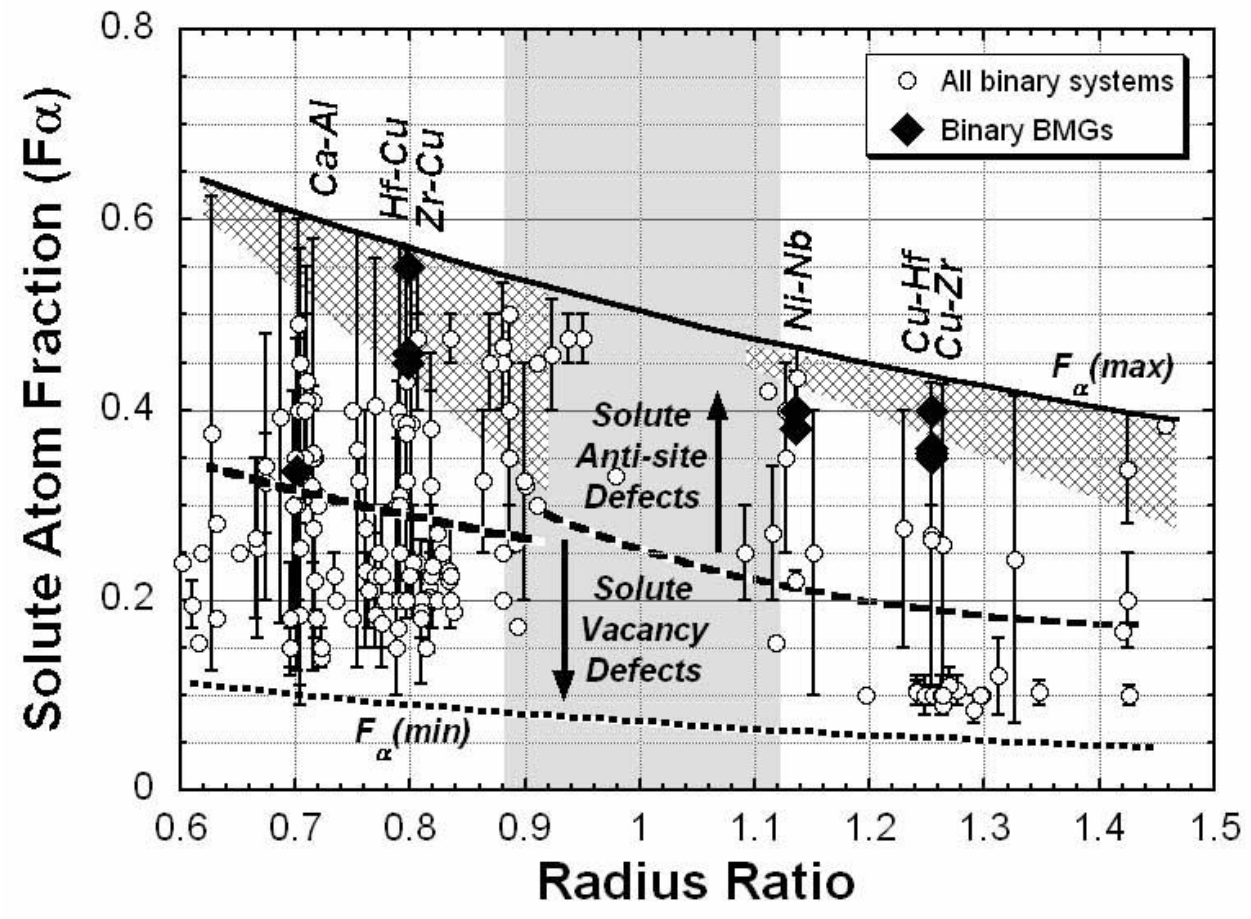



Figure 4 Solute atom fraction vs. nominal radius ratio for all binary metallic glass systems (open symbols) and binary BMGs (filled symbols). The BMG systems are labelled. The solid line is the maximum value of $F_\alpha$ at the iso-structure condition from Equation 11. The dashed line represents the boundary at $\overline{S}_\alpha = 4$ between solute-lean glasses with solute vacancy defects (below) and solute-rich glasses with solute anti-site defects (above). The dotted line is the minimum solute atom fraction at $\overline{S}_\alpha = 1$, where all $\alpha$ sites are filled by $\alpha$. The gray band is the region of poor GFA from the empirical rule that the preferred difference in solvent and solute radii is greater than ±12%. The cross-hatched areas represent regions of maximal global packing efficiency (Section 4.6).

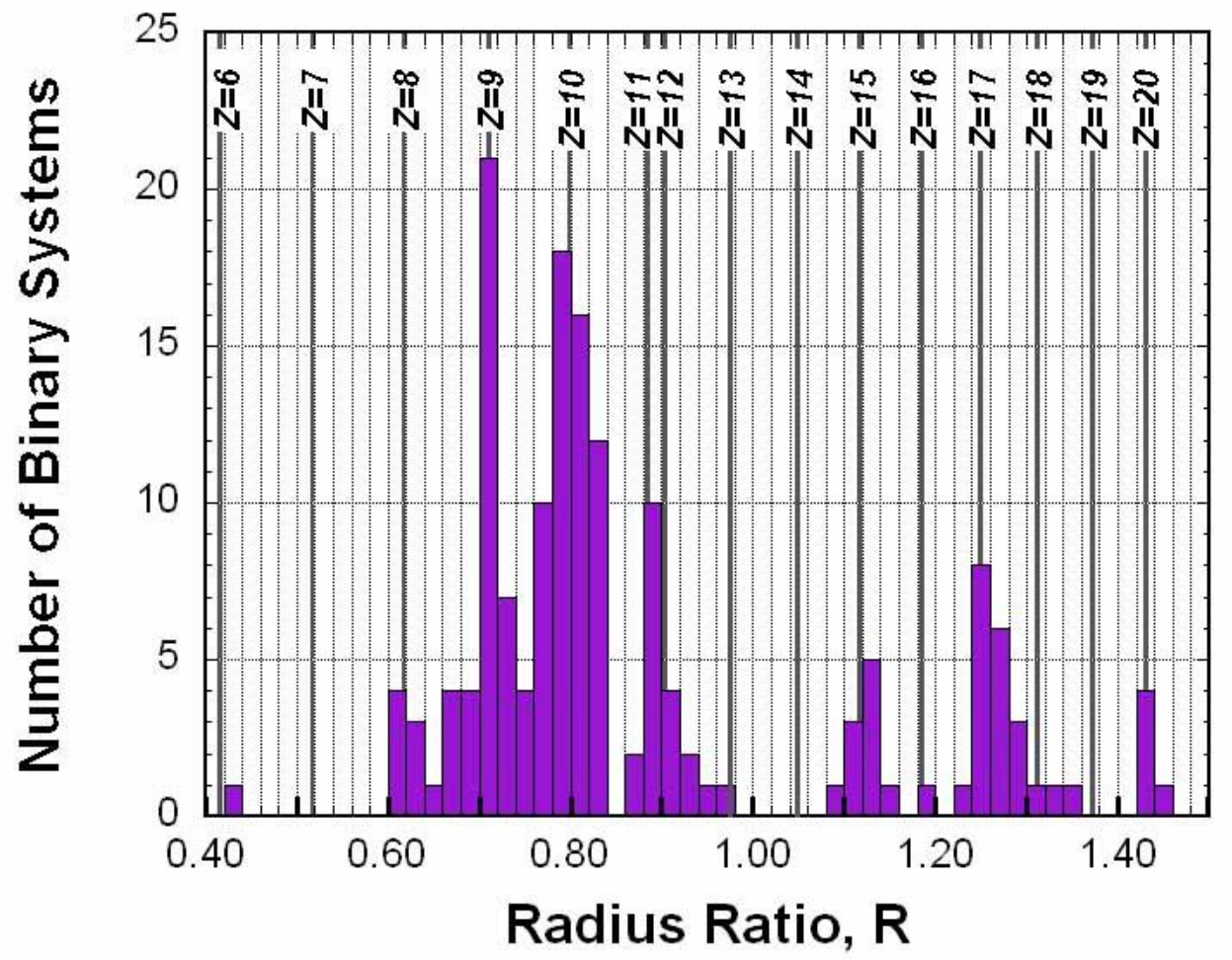



Figure 5 Histogram of the nominal solute-to-solvent radius ratios, $R = r_\alpha / r_\Omega$ , in binary metallic glass systems. The vertical bars represent the number of glass systems with $R$ values in the interval between $R$ and $R$+0.02 as a function of $R$. The bold vertical lines indicate special radius ratios, $R^*$, that give efficient local atomic packing of $Z$ solvent atoms around a central $\alpha$ solute.

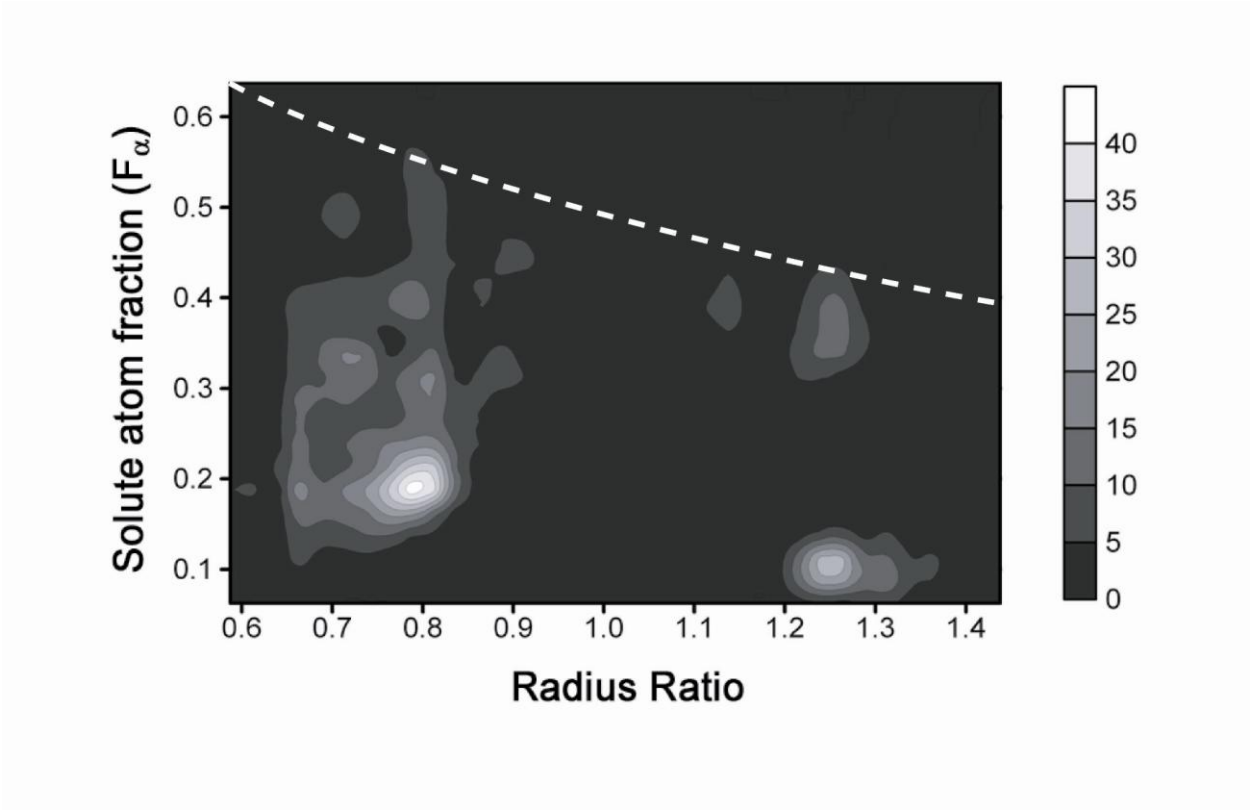



Figure 6 Contour plot of the number of reported alloys within increments $R$+0.05$R$ and $F_\alpha$+0.05$F_\alpha$ as a function of $R$ and $F_\alpha$. The dashed line represents the maximum solute atom fraction at the iso-structural condition from Equation 11.

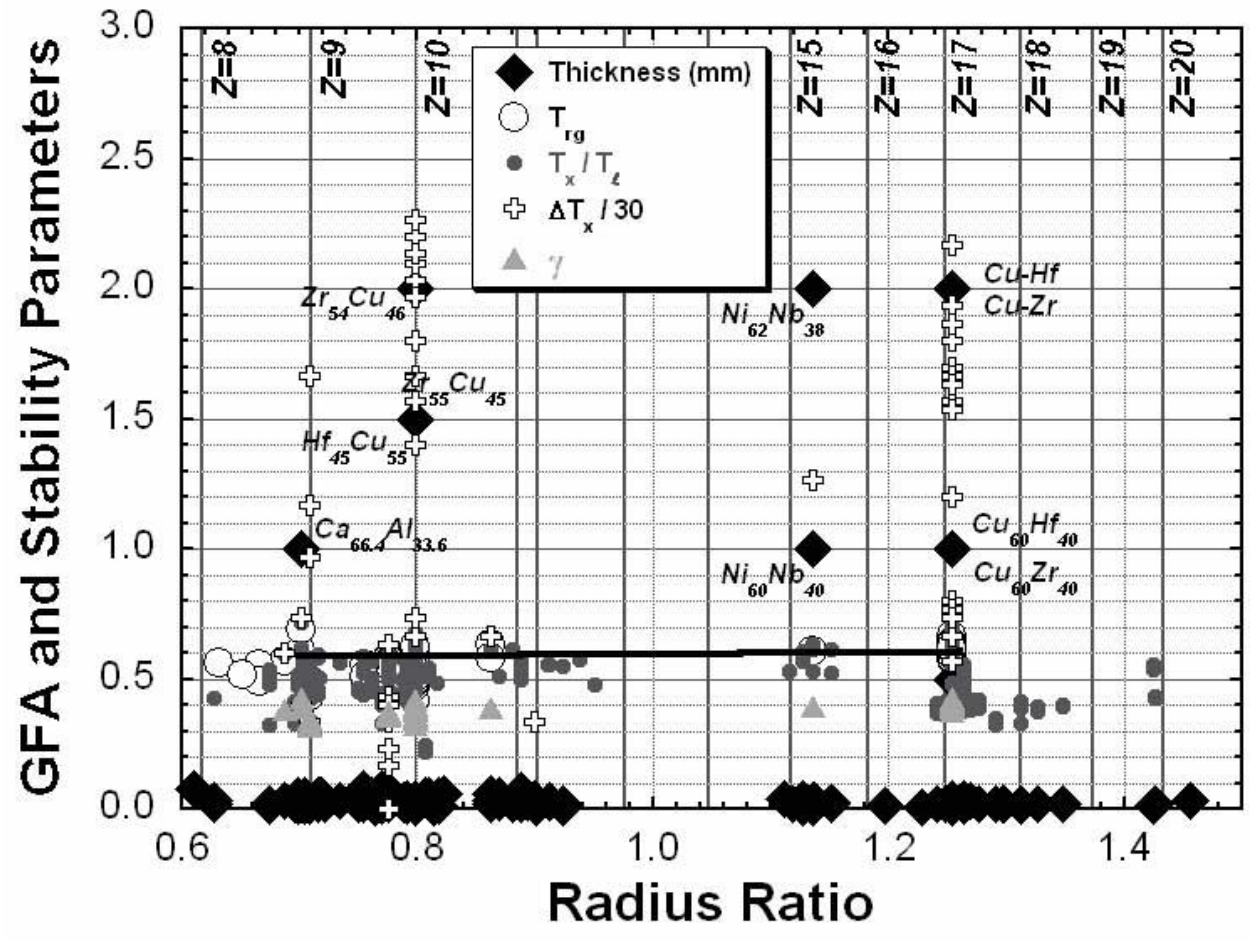



Figure 7 GFA and thermal stability parameters v. $R$. Values of $R^*$ are shown by the vertical lines. The solid line shows a linear regression from the $T_{rg}$ datapoints for the binary BMGs only. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

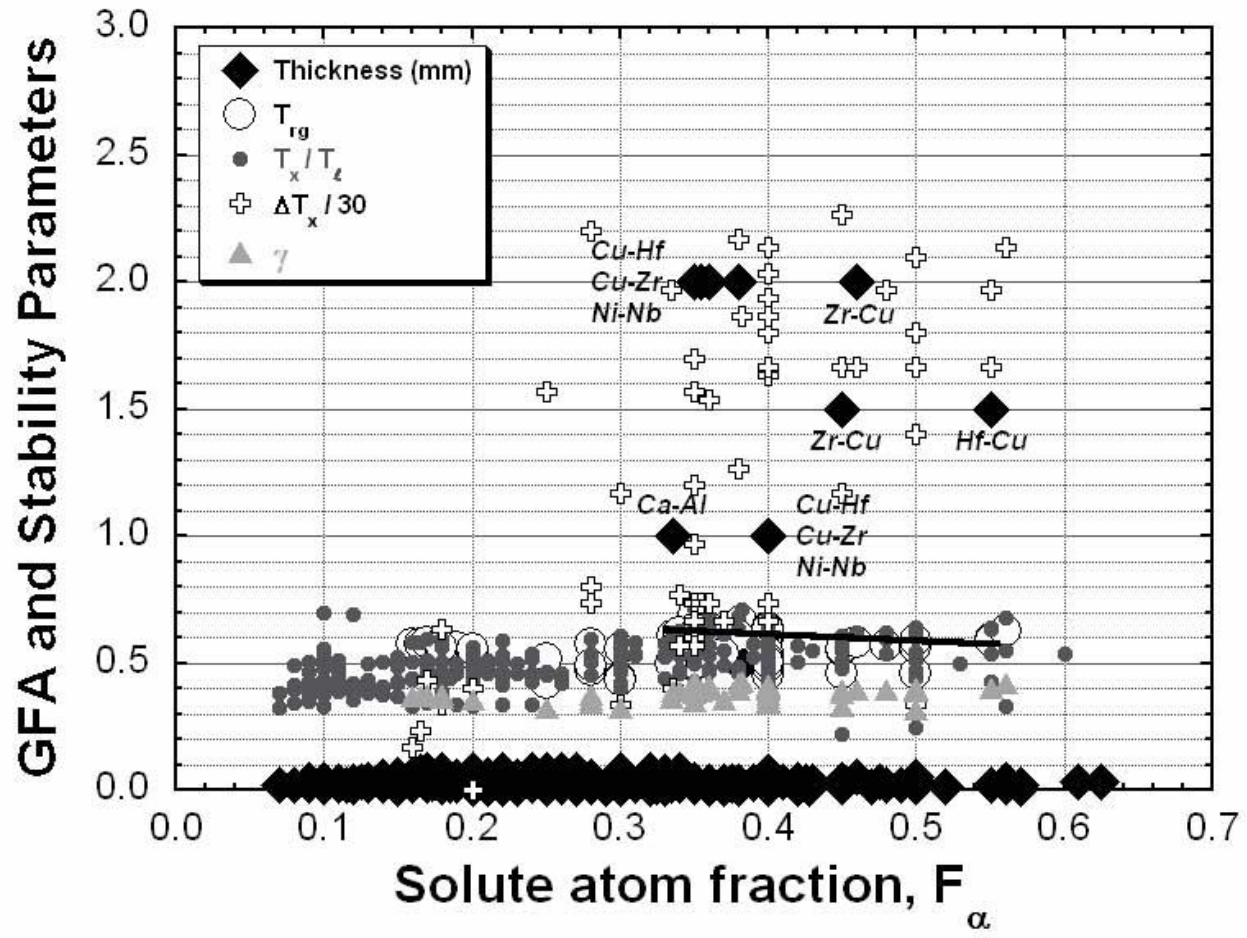



Figure 8 GFA and thermal stability parameters v. $F_\alpha$. The solid line shows a linear regression from the $T_{rg}$ datapoints for the binary BMGs only. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

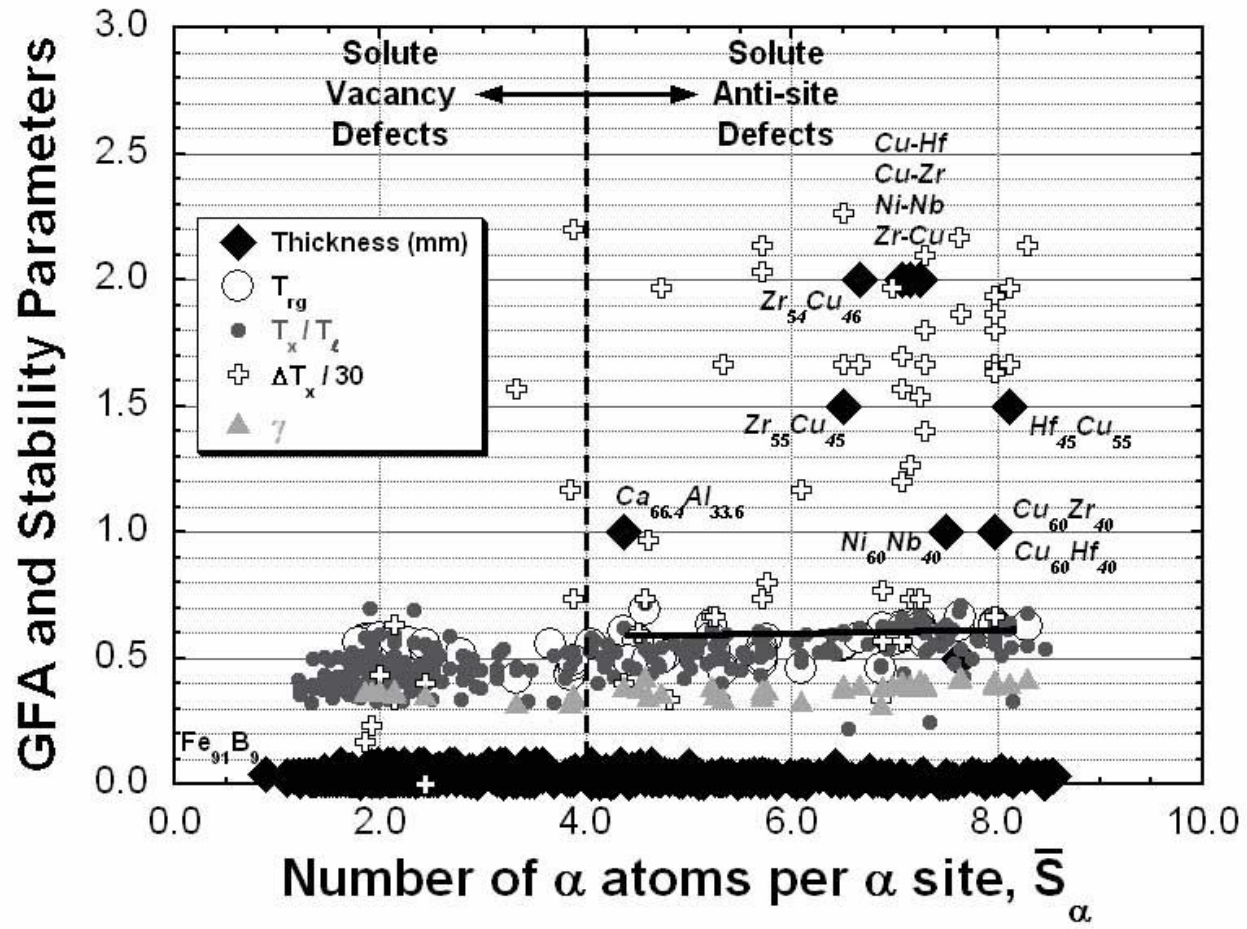



Figure 9 GFA and thermal stability parameters v. the number of α atoms in the structure per α site, $\bar{S}_\alpha$. All solute sites are filled when $\bar{S}_\alpha = 4$, which defines the boundary between solute-lean and solute-rich structures. The solid line shows a linear regression from the $T_{rg}$ datapoints for the binary BMGs only. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

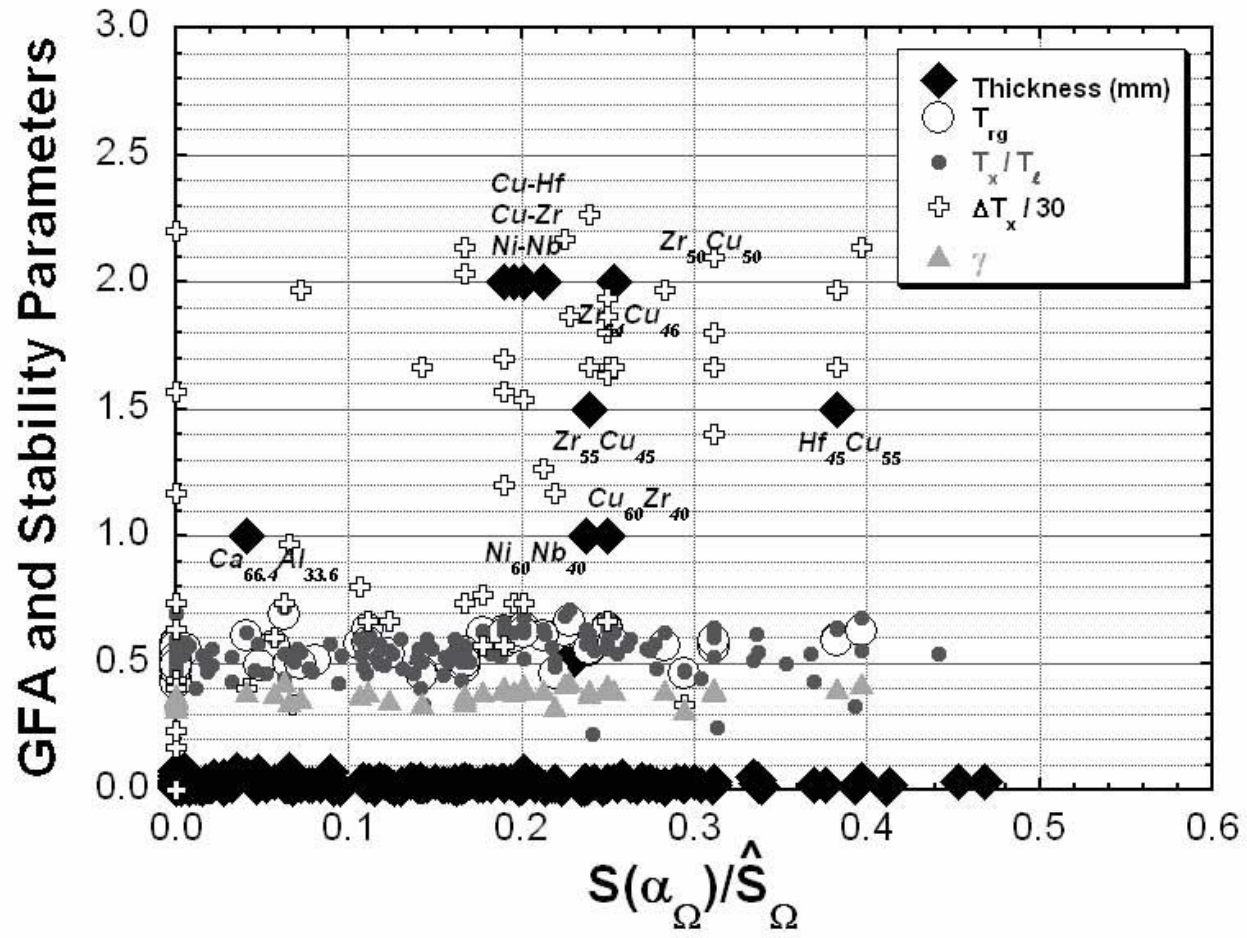



Figure 10 GFA and thermal stability parameters v. the fraction of Ω sites in the structure that are occupied by α atoms. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

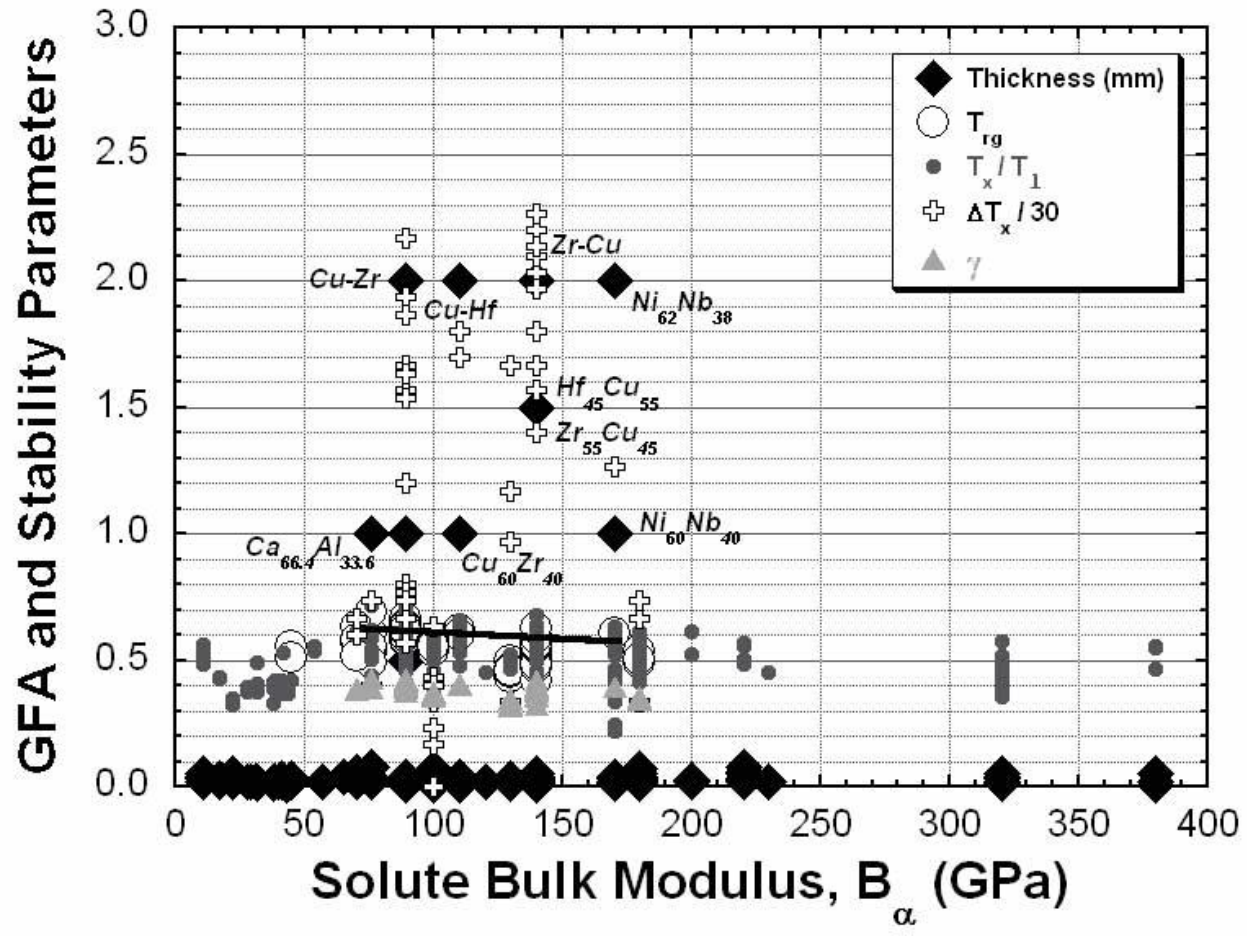



Figure 11 GFA and thermal stability parameters v. the solute bulk modulus, $B_\alpha$. The solid line shows a linear regression from the $T_{rg}$ datapoints for the binary BMGs only. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

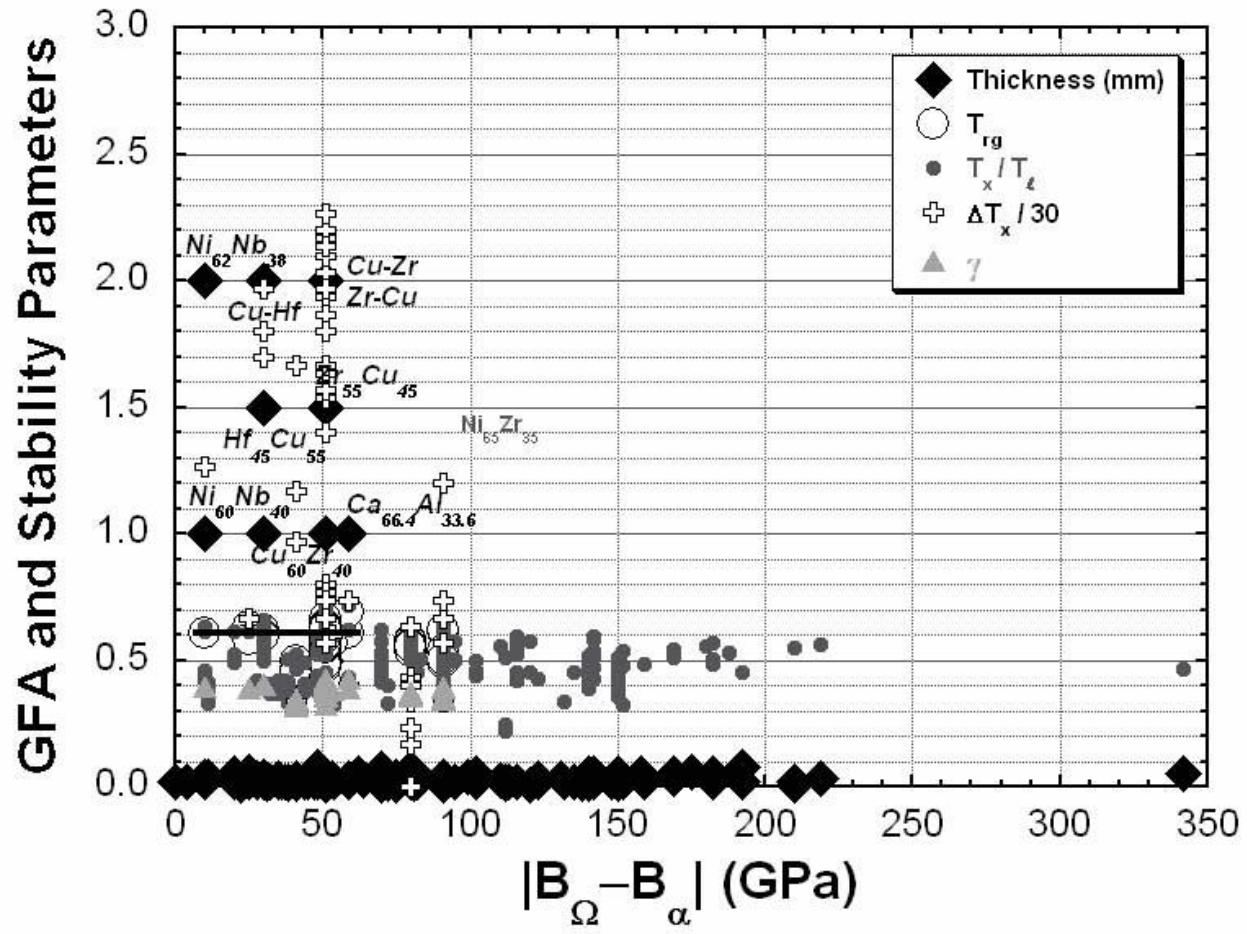



Figure 12 GFA and thermal stability parameters v. the absolute difference in solvent and solute bulk moduli. The solid line shows a linear regression from the $T_{rg}$ datapoints for the binary BMGs only. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

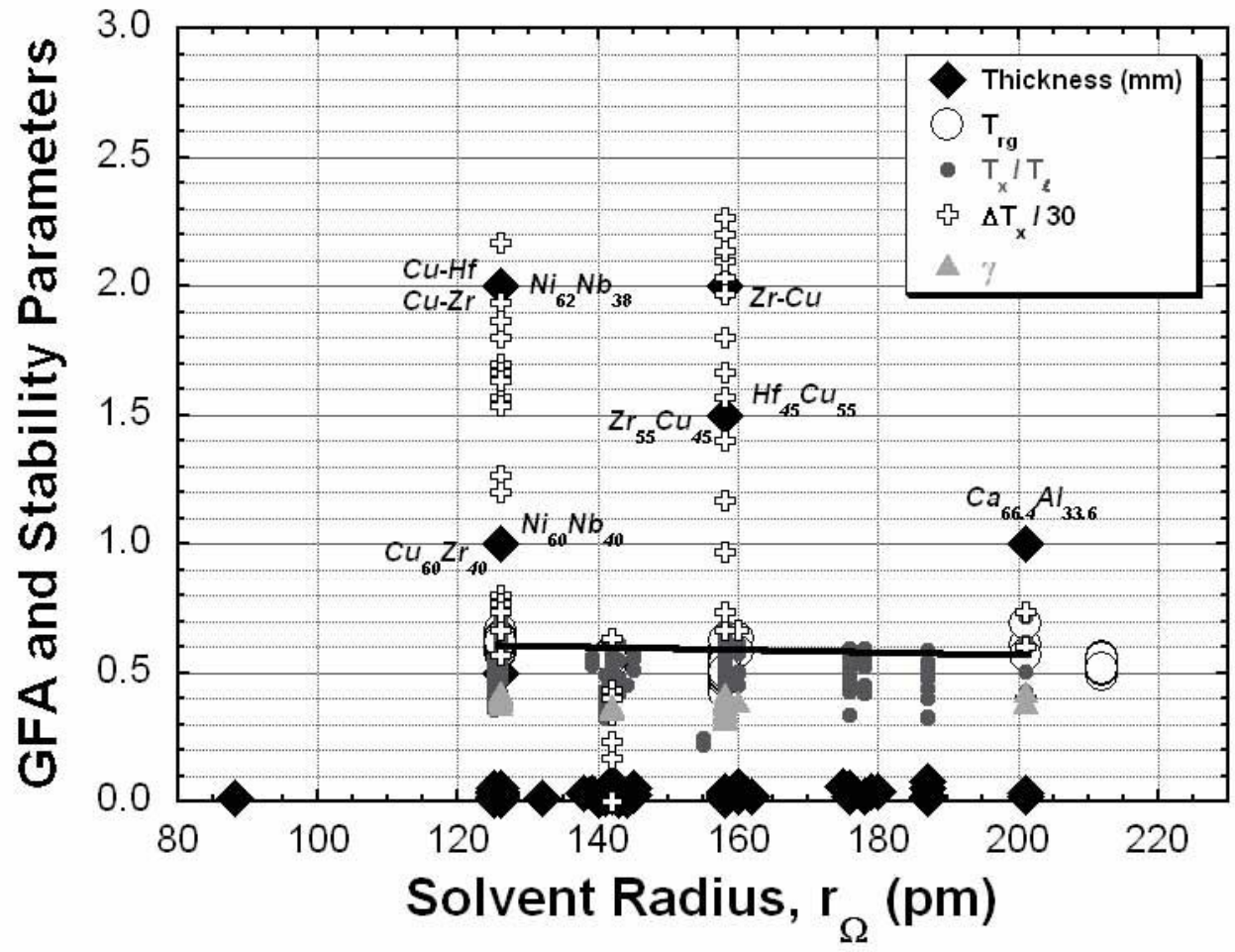



Figure 13 GFA and thermal stability parameters v. the solvent atom radius, $r_\Omega$. The solid curve is a linear regression fit to $T_{rg}$ datapoints for binary BMGs only. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

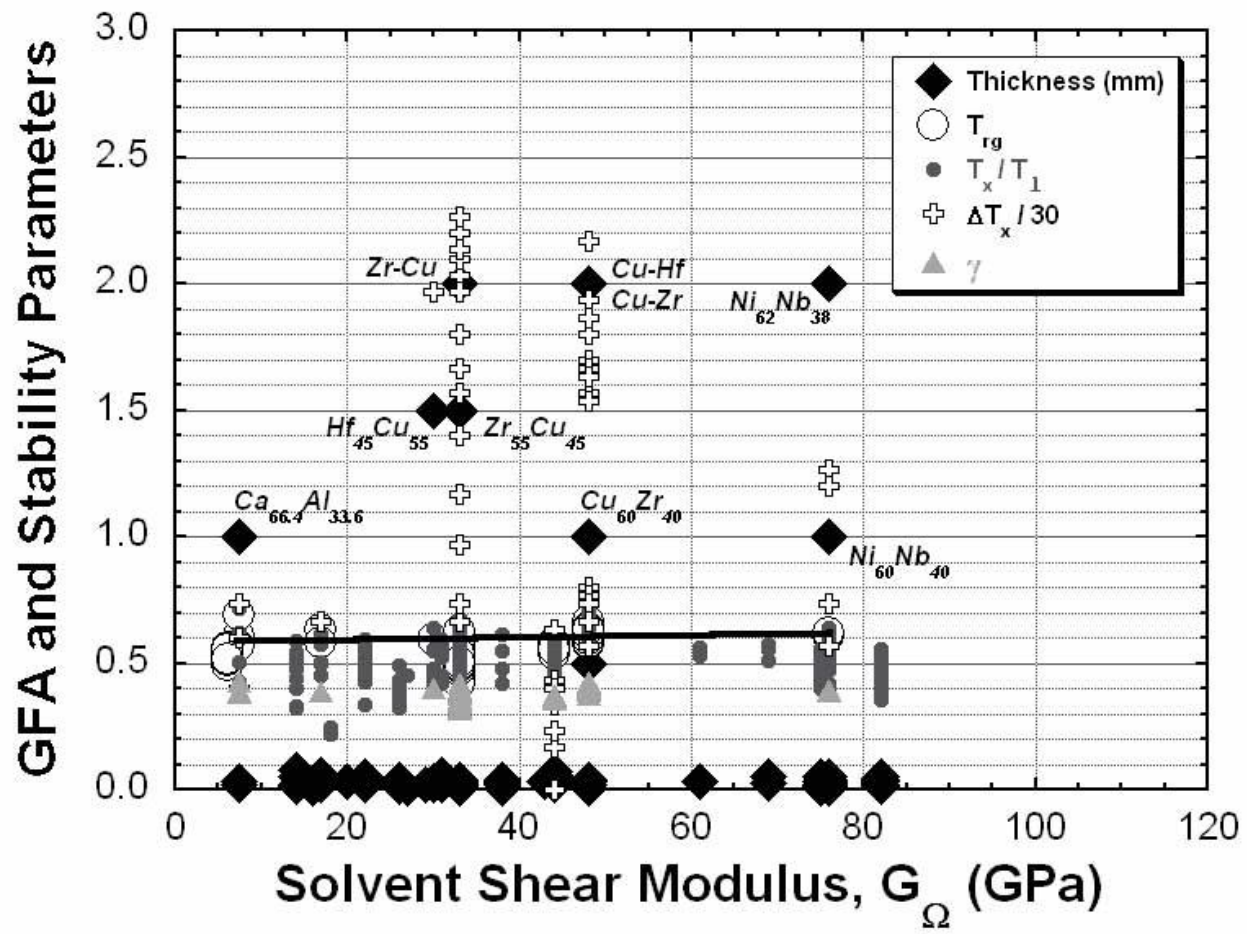



Figure 14 GFA and thermal stability parameters v. the solvent shear modulus, $G_\Omega$. The solid curve is a linear regression fit to $T_{rg}$ datapoints for binary BMGs only. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

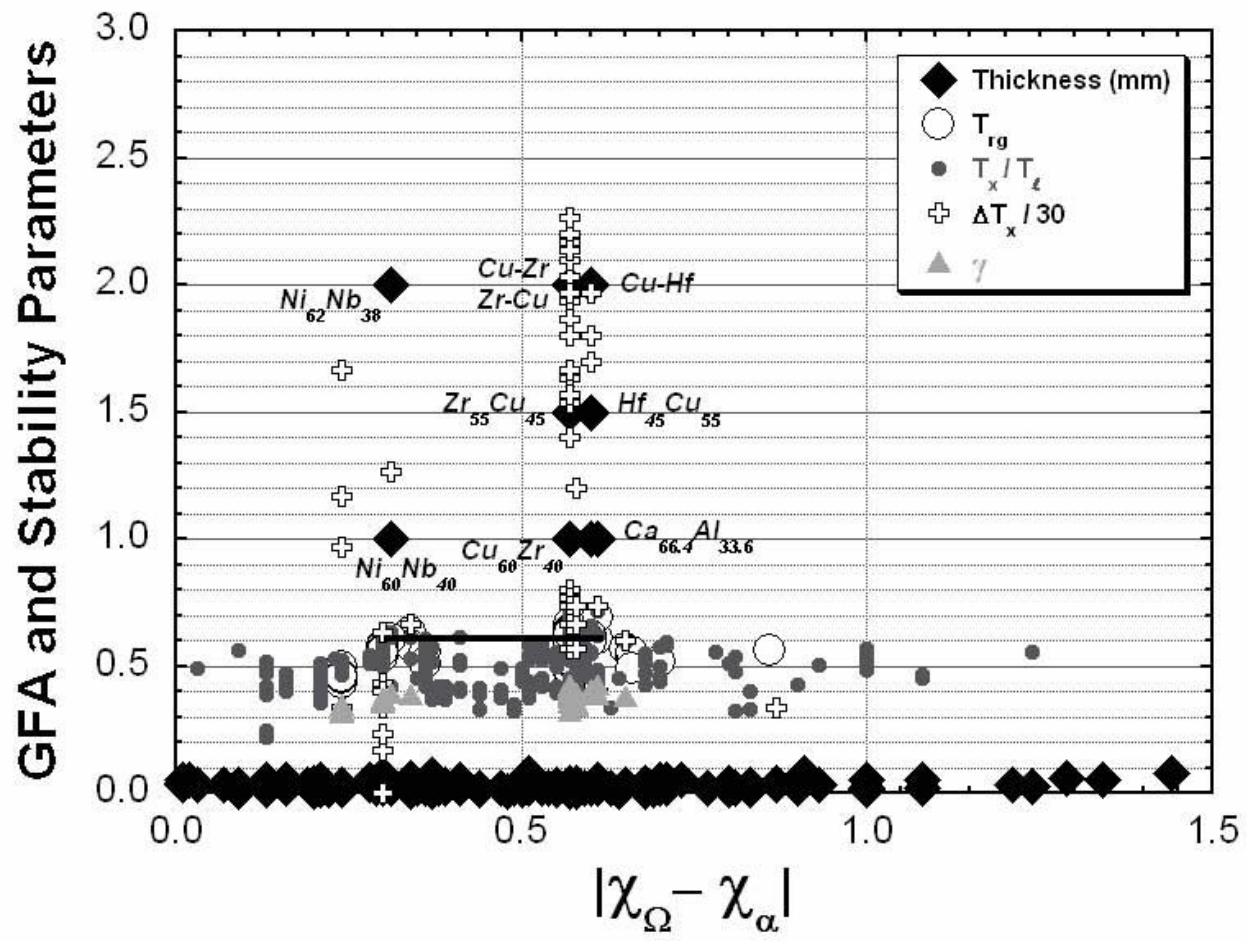



Figure 15 GFA and thermal stability parameters v. the absolute difference in solute and solvent Pauling electronegativities. The solid curve is a linear regression fit to $T_{rg}$ datapoints for binary BMGs only. For convenience, $\Delta T_x$ is reduced by a factor of 30 to fit the same scale.

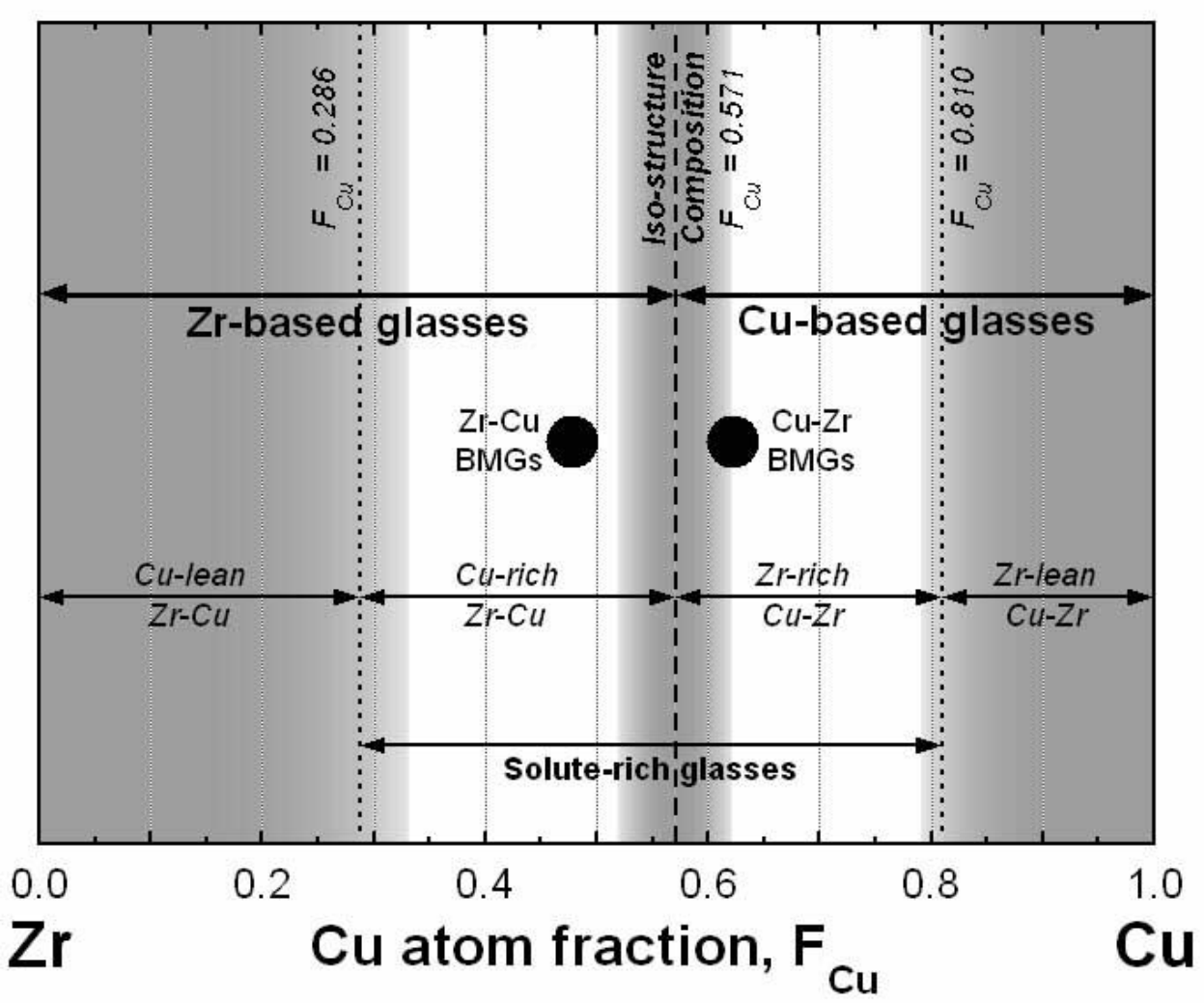



Figure 16 Illustration of composition ranges for Zr-Cu and Cu-Zr binary systems. Solute-rich Zr-Cu BMGs and solute-rich Cu-Zr BMGs both approach the iso-structural composition. The iso-structural composition and the compositions of the boundaries between solute-rich and solute lean structures depend explicitly on the radius ratio of the glass system.

## Appendix

**Table A1. Binary metallic glass constitutions, densities, characteristic temperatures and structural parameters.**

| Ω | α | $F_\alpha$ | R | ρ, g cm$^{-3}$ | $T_g$, K | $T_x$, K | $T_l$, K | $T_{rg}$ | $\Delta T_x$ | $T_x/T_\ell$ | γ | $\hat{S}_\Omega$ | $\bar{S}_\alpha$ | $\bar{S}_\Omega$ | $S(\alpha_\alpha)$ | $S(\alpha_\beta)$ | $S(\alpha_\gamma)$ | $S(\alpha_\Omega)$ | $Z_{\alpha\alpha}$ | $Z_{\alpha\Omega}$ | $Z_{\Omega\alpha}$ | $Z_{\Omega\Omega}$ | Citations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Al | Ca | 0.090 | 1.426 | | | 408 | 955 | | 0.427 | | | 19.88 | 1.97 | 19.88 | 1 | 0.97 | 0 | 0 | | | | | [26] |
| Al | Ca | 0.100 | 1.426 | | | 419 | 973 | | 0.431 | | | 19.88 | 2.21 | 19.88 | 1 | 1 | 0.21 | 0 | | | | | [26] |
| Al | Ca | 0.110 | 1.426 | | | 425 | 1003 | | 0.424 | | | 19.88 | 2.46 | 19.88 | 1 | 1 | 0.46 | 0 | | | | | [26] |
| Al | Ce | 0.070 | 1.291 | | | 437 | 1360 | | 0.321 | | | 17.67 | 1.33 | 17.67 | 1 | 0.33 | 0 | 0 | | | | | [27] |
| Al | Ce | 0.080 | 1.291 | | | 468 | 1370 | | 0.342 | | | 17.67 | 1.54 | 17.67 | 1 | 0.54 | 0 | 0 | | | | | [27] |
| Al | Ce | 0.090 | 1.291 | | | 483 | 1390 | | 0.347 | | | 17.67 | 1.75 | 17.67 | 1 | 0.75 | 0 | 0 | | | | | [27] |
| Al | Ce | 0.100 | 1.291 | | | 463 | 1410 | | 0.328 | | | 17.67 | 1.96 | 17.67 | 1 | 0.96 | 0 | 0 | | | | | [27] |
| Al | Cu | 0.173 | 0.894 | | | | | | | | | 11.12 | 2.33 | 11.12 | 1 | 1 | 0.33 | 0 | | | | | [28] |
| Al | Dy | 0.090 | 1.241 | | | 478 | 1278 | | 0.374 | | | 16.89 | 1.67 | 16.89 | 1 | 0.67 | 0 | 0 | | | | | [29] |
| Al | Dy | 0.100 | 1.241 | | | 520 | 1353 | | 0.384 | | | 16.89 | 1.88 | 16.89 | 1 | 0.88 | 0 | 0 | | | | | [29] |
| Al | Dy | 0.110 | 1.241 | | | 530 | 1363 | | 0.389 | | | 16.89 | 2.09 | 16.89 | 1 | 1 | 0.09 | 0 | | | | | [29] |
| Al | Dy | 0.120 | 1.241 | | | 515 | 1393 | | 0.370 | | | 16.89 | 2.30 | 16.89 | 1 | 1 | 0.3 | 0 | | | | | [29] |
| Al | Er | 0.090 | 1.241 | | | 435 | 1183 | | 0.368 | | | 16.89 | 1.67 | 16.89 | 1 | 0.67 | 0 | 0 | | | | | [29] |
| Al | Er | 0.100 | 1.241 | | | 460 | 1193 | | 0.386 | | | 16.89 | 1.88 | 16.89 | 1 | 0.88 | 0 | 0 | | | | | [29] |
| Al | Er | 0.115 | 1.241 | | | 505 | 1233 | | 0.410 | | | 16.89 | 2.19 | 16.89 | 1 | 1 | 0.19 | 0 | | | | | [29] |
| Al | Gd | 0.080 | 1.248 | | | 470 | 1133 | | 0.415 | | | 17.00 | 1.48 | 17.00 | 1 | 0.48 | 0 | 0 | | | | | [29] |
| Al | Gd | 0.100 | 1.248 | | | 505 | 1223 | | 0.413 | | | 17.00 | 1.89 | 17.00 | 1 | 0.89 | 0 | 0 | | | | | [29] |
| Al | Gd | 0.120 | 1.248 | | | 510 | 1273 | | 0.401 | | | 17.00 | 2.32 | 17.00 | 1 | 1 | 0.32 | 0 | | | | | [29] |
| Al | Ho | 0.090 | 1.255 | | | 445 | 1192 | | 0.373 | | | 17.11 | 1.69 | 17.11 | 1 | 0.69 | 0 | 0 | | | | | [29] |
| Al | Ho | 0.100 | 1.255 | | | 495 | 1223 | | 0.405 | | | 17.11 | 1.90 | 17.11 | 1 | 0.9 | 0 | 0 | | | | | [29] |
| Al | Ho | 0.110 | 1.255 | | | 530 | 1253 | | 0.423 | | | 17.11 | 2.12 | 17.11 | 1 | 1 | 0.12 | 0 | | | | | [29] |

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| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Al | La | 0.070 | 1.326 | | | 442 | 1153 | | 0.383 | | | 18.24 | 1.37 | 18.24 | 1 | 0.37 | 0 | 0 | | | | | | [29, 30] |
| Al | La | 0.080 | 1.326 | | | 472 | 1188 | | 0.397 | | | 18.24 | 1.59 | 18.24 | 1 | 0.59 | 0 | 0 | | | | | | [29] |
| Al | La | 0.090 | 1.326 | | | 480 | 1233 | | 0.389 | | | 18.24 | 1.80 | 18.24 | 1 | 0.8 | 0 | 0 | | | | | | [29] |
| Al | La | 0.100 | 1.326 | | | 477 | 1273 | | 0.375 | | | 18.24 | 2.03 | 18.24 | 1 | 1 | 0.03 | 0 | | | | | | [29, 31] |
| Al | La | 0.140 | 1.326 | | | 540 | 1418 | | 0.381 | | | 18.24 | 2.97 | 18.24 | 1 | 1 | 0.97 | 0 | | | | | | [30] |
| Al | La | 0.414 | 1.326 | | | | | | | | | 16.53 | 8.50 | 12.03 | 1 | 1 | 2 | 4.5 | | | | | | [30] |
| Al | Nd | 0.080 | 1.262 | | | 450 | 913 | | 0.493 | | | 17.22 | 1.50 | 17.22 | 1 | 0.5 | 0 | 0 | | | | | | [29, 32] |
| Al | Nd | 0.100 | 1.262 | | | 500 | 1223 | | 0.409 | | | 17.22 | 1.91 | 17.22 | 1 | 0.91 | 0 | 0 | | | | | | [29, 32] |
| Al | Nd | 0.120 | 1.262 | | | 511 | 1373 | | 0.372 | | | 17.22 | 2.35 | 17.22 | 1 | 1 | 0.35 | 0 | | | | | | [29, 32] |
| Al | Pr | 0.100 | 1.298 | | | | | | | | | 17.79 | 1.98 | 17.79 | 1 | 0.98 | 0 | 0 | | | | | | [29] |
| Al | Sm | 0.080 | 1.312 | | | 455 | 1133 | | 0.402 | | | 18.01 | 1.57 | 18.01 | 1 | 0.57 | 0 | 0 | | | | | | [29, 33] |
| Al | Sm | 0.100 | 1.312 | | | 493 | 1200 | | 0.411 | | | 18.01 | 2.00 | 18.01 | 1 | 1 | 0 | 0 | | | | | | [29] |
| Al | Sm | 0.120 | 1.312 | | | 505 | 1253 | | 0.403 | | | 18.01 | 2.46 | 18.01 | 1 | 1 | 0.46 | 0 | | | | | | [29] |
| Al | Sm | 0.140 | 1.312 | | | 509 | 1313 | | 0.388 | | | 18.01 | 2.93 | 18.01 | 1 | 1 | 0.93 | 0 | | | | | | [29] |
| Al | Sm | 0.160 | 1.312 | | | 502 | 1513 | | 0.332 | | | 18.01 | 3.43 | 18.01 | 1 | 1 | 1.43 | 0 | | | | | | [29] |
| Al | Tb | 0.090 | 1.277 | | | 468 | 1203 | | 0.389 | | | 17.45 | 1.73 | 17.45 | 1 | 0.73 | 0 | 0 | | | | | | [29] |
| Al | Tb | 0.100 | 1.277 | | | 502 | 1243 | | 0.404 | | | 17.45 | 1.94 | 17.45 | 1 | 0.94 | 0 | 0 | | | | | | [29] |
| Al | Tb | 0.110 | 1.277 | | | 535 | 1273 | | 0.420 | | | 17.45 | 2.16 | 17.45 | 1 | 1 | 0.16 | 0 | | | | | | [29] |
| Al | Tb | 0.120 | 1.277 | | | 505 | 1293 | | 0.391 | | | 17.45 | 2.38 | 17.45 | 1 | 1 | 0.38 | 0 | | | | | | [29] |
| Al | Y | 0.090 | 1.27 | | | 437 | 1153 | | 0.379 | | | 17.34 | 1.71 | 17.34 | 1 | 0.71 | 0 | 0 | | | | | | [27] |
| Al | Y | 0.100 | 1.27 | | | 496 | 1174 | | 0.422 | | | 17.34 | 1.93 | 17.34 | 1 | 0.93 | 0 | 0 | 10.7 | 1.6 | 14.1 | 1.1 | [27, 34] |
| Al | Y | 0.110 | 1.27 | | | 502 | 1213 | | 0.414 | | | 17.34 | 2.14 | 17.34 | 1 | 1 | 0.14 | 0 | | | | | | [27] |
| Al | Y | 0.120 | 1.27 | | | 526 | 1243 | | 0.423 | | | 17.34 | 2.36 | 17.34 | 1 | 1 | 0.36 | 0 | | | | | | [27] |
| Al | Y | 0.130 | 1.27 | | | 518 | 1283 | | 0.404 | | | 17.34 | 2.59 | 17.34 | 1 | 1 | 0.59 | 0 | | | | | | [27] |
| Al | Yb | 0.090 | 1.348 | | | 450 | 1133 | | 0.397 | | | 18.59 | 1.84 | 18.59 | 1 | 0.84 | 0 | 0 | | | | | | [29] |
| Al | Yb | 0.100 | 1.348 | | | 455 | 1153 | | 0.395 | | | 18.59 | 2.07 | 18.59 | 1 | 1 | 0.07 | 0 | | | | | | [29] |
| Al | Yb | 0.115 | 1.348 | | | 480 | 1198 | | 0.401 | | | 18.59 | 2.42 | 18.59 | 1 | 1 | 0.42 | 0 | | | | | | [29] |
| Au | Si | 0.170 | 0.764 | | | | | | | | | 9.60 | 1.97 | 9.60 | 1 | 0.97 | 0 | 0 | | | | | | [35] |
| Au | Si | 0.186 | 0.764 | | | 280 | 623 | | 0.449 | | | 9.60 | 2.19 | 9.60 | 1 | 1 | 0.19 | 0 | | | | | | [36] |
| Au | Si | 0.200 | 0.764 | | | | | | | | | 9.60 | 2.40 | 9.60 | 1 | 1 | 0.4 | 0 | | | | | | [35] |
| Au | Si | 0.250 | 0.764 | | | | | | | | | 9.60 | 3.20 | 9.60 | 1 | 1 | 1.2 | 0 | | | | | | [37] |
| B | N | 0.220 | 0.818 | | | | | | | | | 10.22 | 2.88 | 10.22 | 1 | 1 | 0.88 | 0 | | | | | | [38] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B | N | 0.420 | 0.818 | | | | | | | | | 10.59 | 6.13 | 8.46 | 1 | 1 | 2 | 2.13 | | | | | [38] |
| Ba | Al | 0.280 | 0.632 | | | | | | | | | 8.17 | 3.18 | 8.17 | 1 | 1 | 1.18 | 0 | | | | | [39] |
| Ba | Ga | 0.240 | 0.601 | | | | | | | | | 7.84 | 2.48 | 7.84 | 1 | 1 | 0.48 | 0 | | | | | [39] |
| Ba | Mg | 0.350 | 0.717 | | | | | | | | | 9.24 | 4.63 | 8.61 | 1 | 1 | 2 | 0.63 | | | | | [39] |
| Ba | Zn | 0.250 | 0.619 | | | | | | | | | 8.02 | 2.67 | 8.02 | 1 | 1 | 0.67 | 0 | | | | | [39] |
| Ca | Ag | 0.125 | 0.716 | | | | | | | | | 9.07 | 1.30 | 9.07 | 1 | 0.3 | 0 | 0 | | | | | [40] |
| Ca | Ag | 0.350 | 0.716 | | | 438 | 868 | | 0.505 | | | 9.23 | 4.63 | 8.60 | 1 | 1 | 2 | 0.63 | | | | | [40, 41] |
| Ca | Ag | 0.425 | 0.716 | | | | | | | | | 9.51 | 5.74 | 7.77 | 1 | 1 | 2 | 1.74 | | | | | [40] |
| Ca | Al | 0.125 | 0.701 | | | | | | | | | 8.91 | 1.27 | 8.91 | 1 | 0.27 | 0 | 0 | | | | | [40] |
| Ca | Al | 0.336 | 0.701 | | 528 | 540 | 873 | 0.605 | 0.619 | 12 | 0.385 | 9.00 | 4.37 | 8.63 | 1 | 1 | 2 | 0.37 | | | | | [42] |
| Ca | Al | 0.350 | 0.701 | | 563 | 585 | 818 | 0.688 | 0.715 | 22 | 0.424 | 9.05 | 4.57 | 8.49 | 1 | 1 | 2 | 0.57 | | | | | [39, 40] |
| Ca | Al | 0.400 | 0.701 | 1.96 | | | | | | | | 9.25 | 5.30 | 7.95 | 1 | 1 | 2 | 1.3 | | | | | [43] |
| Ca | Al | 0.475 | 0.701 | | | | | | | | | 9.55 | 6.44 | 7.11 | 1 | 1 | 2 | 2.44 | | | | | [40] |
| Ca | Au | 0.350 | 0.716 | | | | | | | | | 9.23 | 4.63 | 8.60 | 1 | 1 | 2 | 0.63 | | | | | [41] |
| Ca | Cu | 0.125 | 0.627 | | | | | | | | | 8.11 | 1.16 | 8.11 | 1 | 0.16 | 0 | 0 | | | | | [40] |
| Ca | Cu | 0.300 | 0.627 | 1.81 | | | | | | | | 8.11 | 3.48 | 8.11 | 1 | 1 | 1.48 | 0 | | | | | [44] |
| Ca | Cu | 0.350 | 0.627 | | | 441 | 1033 | | 0.427 | | | 8.19 | 4.27 | 7.92 | 1 | 1 | 2 | 0.27 | | | | | [40, 41] |
| Ca | Cu | 0.500 | 0.627 | | | | | | | | | 8.87 | 6.44 | 6.44 | 1 | 1 | 2 | 2.44 | | | | | [40] |
| Ca | Cu | 0.625 | 0.627 | | | | | | | | | 9.55 | 8.47 | 5.08 | 1 | 1 | 2 | 4.47 | | | | | [40] |
| Ca | Ga | 0.160 | 0.667 | | | | | | | | | 8.53 | 1.62 | 8.53 | 1 | 0.62 | 0 | 0 | | | | | [39] |
| Ca | Ga | 0.350 | 0.667 | | | | | | | | | 8.65 | 4.43 | 8.22 | 1 | 1 | 2 | 0.43 | | | | | [41] |
| Ca | Mg | 0.225 | 0.796 | | | | | | | | | 9.97 | 2.89 | 9.97 | 1 | 1 | 0.89 | 0 | | | | | [40] |
| Ca | Mg | 0.270 | 0.796 | | | | | | | | | 9.97 | 3.69 | 9.97 | 1 | 1 | 1.69 | 0 | | | | | [39] |
| Ca | Mg | 0.300 | 0.796 | 1.45 | | | | | | | | 10.00 | 4.20 | 9.80 | 1 | 1 | 2 | 0.2 | | | | | [44] |
| Ca | Mg | 0.350 | 0.796 | | | 414 | 987 | | 0.419 | | | 10.15 | 4.95 | 9.19 | 1 | 1 | 2 | 0.95 | | | | | [40, 41] |
| Ca | Mg | 0.400 | 0.796 | 1.47 | | | | | | | | 10.29 | 5.72 | 8.57 | 1 | 1 | 2 | 1.72 | | | | | [43] |
| Ca | Mg | 0.425 | 0.796 | | | | | | | | | 10.37 | 6.11 | 8.26 | 1 | 1 | 2 | 2.11 | | | | | [40] |
| Ca | Pd | 0.350 | 0.706 | | | | | | | | | 9.11 | 4.59 | 8.52 | 1 | 1 | 2 | 0.59 | | | | | [41] |
| Ca | Zn | 0.175 | 0.687 | | | | | | | | | 8.75 | 1.86 | 8.75 | 1 | 0.86 | 0 | 0 | | | | | [40] |
| Ca | Zn | 0.270 | 0.687 | | | | | | | | | 8.75 | 3.23 | 8.75 | 1 | 1 | 1.23 | 0 | | | | | [39] |
| Ca | Zn | 0.350 | 0.687 | | 389 | 407 | 687 | 0.566 | 0.592 | 18 | 0.378 | 8.88 | 4.51 | 8.37 | 1 | 1 | 2 | 0.51 | | | | | [40] |
| Ca | Zn | 0.500 | 0.687 | | | | | | | | | 9.50 | 6.75 | 6.75 | 1 | 1 | 2 | 2.75 | | | | | [40] |

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ca | Zn | 0.609 | 0.687 | | | | | | | | | 10.01 | 8.53 | 5.48 | 1 | 1 | 2 | 4.53 | | | | [40] |
| Ce | Au | 0.200 | 0.791 | | | | | | | | | 9.91 | 2.48 | 9.91 | 1 | 1 | 0.48 | 0 | | | | [45] |
| Co | B | 0.110 | 0.704 | | | | | | | | | 8.94 | 1.10 | 8.94 | 1 | 0.1 | 0 | 0 | | | | [46] |
| Co | B | 0.120 | 0.704 | | | | | | | | | 8.94 | 1.22 | 8.94 | 1 | 0.22 | 0 | 0 | | | | [46] |
| Co | B | 0.160 | 0.704 | 8.225 | | | | | | | | 8.94 | 1.70 | 8.94 | 1 | 0.7 | 0 | 0 | | | | [46, 47] |
| Co | B | 0.170 | 0.704 | 8.34 | | | | | | | | 8.94 | 1.83 | 8.94 | 1 | 0.83 | 0 | 0 | | | | [48] |
| Co | B | 0.180 | 0.704 | | | 656 | 1403 | | 0.468 | | | 8.94 | 1.96 | 8.94 | 1 | 0.96 | 0 | 0 | | | | [49] |
| Co | B | 0.180 | 0.704 | 8.205 | | 603 | 1403 | | 0.430 | | | 8.94 | 1.96 | 8.94 | 1 | 0.96 | 0 | 0 | | | | [47, 50] |
| Co | B | 0.185 | 0.704 | 8.29 | | 603 | 1383 | | 0.436 | | | 8.94 | 2.03 | 8.94 | 1 | 1 | 0.03 | 0 | | | | [51] |
| Co | B | 0.200 | 0.704 | | | 659 | 1393 | | 0.473 | | | 8.94 | 2.23 | 8.94 | 1 | 1 | 0.23 | 0 | | | | [49] |
| Co | B | 0.200 | 0.704 | 8.11 | | | | | | | | 8.94 | 2.23 | 8.94 | 1 | 1 | 0.23 | 0 | | | | [51] |
| Co | B | 0.200 | 0.704 | 8.185 | | | | | | | | 8.94 | 2.23 | 8.94 | 1 | 1 | 0.23 | 0 | | | | [46, 47] |
| Co | B | 0.220 | 0.704 | | | 660 | 1433 | | 0.461 | | | 8.94 | 2.52 | 8.94 | 1 | 1 | 0.52 | 0 | | | | [49] |
| Co | B | 0.220 | 0.704 | 8.12 | | 638 | 1433 | | 0.445 | | | 8.94 | 2.52 | 8.94 | 1 | 1 | 0.52 | 0 | | | | [47, 50] |
| Co | B | 0.230 | 0.704 | 8.16 | | | | | | | | 8.94 | 2.67 | 8.94 | 1 | 1 | 0.67 | 0 | | | | [48] |
| Co | B | 0.240 | 0.704 | | | 660 | 1468 | | 0.450 | | | 8.94 | 2.82 | 8.94 | 1 | 1 | 0.82 | 0 | | | | [49] |
| Co | B | 0.240 | 0.704 | 8.055 | | | | | | | | 8.94 | 2.82 | 8.94 | 1 | 1 | 0.82 | 0 | | | | [46, 47] |
| Co | B | 0.250 | 0.704 | 8.02 | | | | | | | | 8.94 | 2.98 | 8.94 | 1 | 1 | 0.98 | 0 | | | | [51] |
| Co | B | 0.260 | 0.704 | | | 671 | 1503 | | 0.446 | | | 8.94 | 3.14 | 8.94 | 1 | 1 | 1.14 | 0 | | | | [49] |
| Co | B | 0.260 | 0.704 | | | 690 | 1503 | | 0.459 | | | 8.94 | 3.14 | 8.94 | 1 | 1 | 1.14 | 0 | | | | [50] |
| Co | B | 0.280 | 0.704 | | | 696 | 1538 | | 0.453 | | | 8.94 | 3.47 | 8.94 | 1 | 1 | 1.47 | 0 | | | | [49] |
| Co | B | 0.280 | 0.704 | 7.93 | | | | | | | | 8.94 | 3.47 | 8.94 | 1 | 1 | 1.47 | 0 | | | | [46, 47] |
| Co | B | 0.300 | 0.704 | 7.73 | | | | | | | | 8.94 | 3.83 | 8.94 | 1 | 1 | 1.83 | 0 | | | | [51] |
| Co | B | 0.300 | 0.704 | 7.86 | | | | | | | | 8.94 | 3.83 | 8.94 | 1 | 1 | 1.83 | 0 | | | | [47, 50] |
| Co | B | 0.310 | 0.704 | 7.815 | | | | | | | | 8.94 | 4.01 | 8.93 | 1 | 1 | 2 | 0.01 | | | | [47] |
| Co | B | 0.320 | 0.704 | | | | | | | | | 8.97 | 4.15 | 8.82 | 1 | 1 | 2 | 0.15 | | | | [46] |
| Co | B | 0.330 | 0.704 | | | | | | | | | 9.01 | 4.29 | 8.72 | 1 | 1 | 2 | 0.29 | | | | [46] |
| Co | B | 0.340 | 0.704 | | | | | | | | | 9.05 | 4.44 | 8.61 | 1 | 1 | 2 | 0.44 | | | | [52] |
| Co | B | 0.350 | 0.704 | 7.59 | | | | | | | | 9.08 | 4.58 | 8.50 | 1 | 1 | 2 | 0.58 | | | | [51] |
| Co | B | 0.360 | 0.704 | | | 704 | 1523 | | 0.462 | | | 9.12 | 4.72 | 8.40 | 1 | 1 | 2 | 0.72 | | | | [50, 53] |
| Co | B | 0.380 | 0.704 | | | 725 | 1573 | | 0.461 | | | 9.20 | 5.01 | 8.18 | 1 | 1 | 2 | 1.01 | | | | [50, 53] |
| Co | B | 0.400 | 0.704 | 7.44 | | 647 | 1623 | | 0.399 | | | 9.27 | 5.31 | 7.96 | 1 | 1 | 2 | 1.31 | | | | [50, 51, 53] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Co | P | 0.190 | 0.816 | 7.97 | | | | | | | | 10.20 | 2.39 | 10.20 | 1 | 1 | 0.39 | 0 | | | | | [54, 55] |
| Co | P | 0.200 | 0.816 | | | | | | | | | 10.20 | 2.55 | 10.20 | 1 | 1 | 0.55 | 0 | 0 | 8.9 | 2.23 | 10.1 | [56] |
| Co | P | 0.203 | 0.816 | 7.94 | | | | | | | | 10.20 | 2.60 | 10.20 | 1 | 1 | 0.6 | 0 | | | | | [54] |
| Co | P | 0.220 | 0.816 | 7.89 | | | | | | | | 10.20 | 2.88 | 10.20 | 1 | 1 | 0.88 | 0 | | | | | [54] |
| Co | P | 0.236 | 0.816 | 7.9 | | | | | | | | 10.20 | 3.15 | 10.20 | 1 | 1 | 1.15 | 0 | | | | | [54] |
| Co | Ti | 0.210 | 1.136 | | | | | | | | | 15.28 | 4.05 | 15.23 | 1 | 1 | 2 | 0.05 | | | | | [57] |
| Co | Ti | 0.220 | 1.136 | | | 777 | 1463 | | 0.531 | | | 15.26 | 4.24 | 15.02 | 1 | 1 | 2 | 0.24 | | | | | [57] |
| Co | Ti | 0.230 | 1.136 | | | | | | | | | 15.23 | 4.42 | 14.81 | 1 | 1 | 2 | 0.42 | | | | | [57] |
| Co | Zr | 0.090 | 1.264 | | | 779 | 1543 | | 0.505 | | | 17.25 | 1.71 | 17.25 | 1 | 0.71 | 0 | 0 | | | | | [58] |
| Co | Zr | 0.100 | 1.264 | | | 776 | 1505 | | 0.516 | | | 17.25 | 1.92 | 17.25 | 1 | 0.92 | 0 | 0 | | | | | [58] |
| Co | Zr | 0.100 | 1.264 | | | 833 | 1505 | | 0.553 | | | 17.25 | 1.92 | 17.25 | 1 | 0.92 | 0 | 0 | | | | | [59, 60] |
| Co | Zr | 0.100 | 1.264 | | | 804 | 1505 | | 0.534 | | | 17.25 | 1.92 | 17.25 | 1 | 0.92 | 0 | 0 | | | | | [61] |
| Co | Zr | 0.100 | 1.264 | | | 764 | 1505 | | 0.508 | | | 17.25 | 1.92 | 17.25 | 1 | 0.92 | 0 | 0 | | | | | [62] |
| Co | Zr | 0.110 | 1.264 | | | 768 | 1506 | | 0.510 | | | 17.25 | 2.13 | 17.25 | 1 | 1 | 0.13 | 0 | | | | | [58] |
| Co | Zr | 0.120 | 1.264 | | | | | | | | | 17.25 | 2.35 | 17.25 | 1 | 1 | 0.35 | 0 | | | | | [60] |
| Co | Zr | 0.400 | 1.264 | | | | | | | | | 16.04 | 8.01 | 12.02 | 1 | 1 | 2 | 4.01 | | | | | [63] |
| Co | Zr | 0.426 | 1.264 | | | | | | | | | 15.90 | 8.48 | 11.42 | 1 | 1 | 2 | 4.48 | | | | | [63] |
| Cu | Hf | 0.300 | 1.254 | | | | | | | | | 16.47 | 6.14 | 14.33 | 1 | 1 | 2 | 2.14 | | | | | [64] |
| Cu | Hf | 0.350 | 1.254 | | 781 | 832 | 1259 | 0.621 | 0.661 | 51 | 0.408 | 16.20 | 7.07 | 13.13 | 1 | 1 | 2 | 3.07 | | | | | [65] |
| Cu | Hf | 0.400 | 1.254 | | 773 | 827 | 1290 | 0.599 | 0.641 | 54 | 0.401 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | | | | | [64, 66] |
| Cu | Hf | 0.428 | 1.254 | | | | | | | | | 15.80 | 8.47 | 11.32 | 1 | 1 | 2 | 4.47 | | | | | [64] |
| Cu | Te | 0.420 | 1.111 | | | | | | | | | 14.47 | 7.76 | 10.71 | 1 | 1 | 2 | 3.76 | | | | | [67] |
| Cu | Ti | 0.250 | 1.127 | | | | | | | | | 15.05 | 4.76 | 14.29 | 1 | 1 | 2 | 0.76 | | | | | [68] |
| Cu | Ti | 0.270 | 1.127 | | | | | | | | | 15.00 | 5.13 | 13.87 | 1 | 1 | 2 | 1.13 | | | | | [68, 69] |
| Cu | Ti | 0.300 | 1.127 | | | 692 | 1143 | | 0.605 | | | 14.92 | 5.68 | 13.25 | 1 | 1 | 2 | 1.68 | | | | | [68-71] |
| Cu | Ti | 0.340 | 1.127 | | | 697 | 1173 | | 0.594 | | | 14.82 | 6.40 | 12.42 | 1 | 1 | 2 | 2.4 | | | | | [71] |
| Cu | Ti | 0.350 | 1.127 | | | | | | | | | 14.80 | 6.58 | 12.22 | 1 | 1 | 2 | 2.58 | | | | | [70] |
| Cu | Ti | 0.400 | 1.127 | 6.69 | | | | | | | | 14.67 | 7.47 | 11.20 | 1 | 1 | 2 | 3.47 | | | | | [68, 69, 72] |
| Cu | Ti | 0.420 | 1.127 | | | 701 | 1228 | | 0.571 | | | 14.63 | 7.82 | 10.80 | 1 | 1 | 2 | 3.82 | | | | | [71] |
| Cu | Ti | 0.430 | 1.127 | | | | | | | | | 14.60 | 8.00 | 10.60 | 1 | 1 | 2 | 4 | | | | | [73] |
| Cu | Ti | 0.450 | 1.127 | | | | | | | | | 14.55 | 8.35 | 10.20 | 1 | 1 | 2 | 4.35 | | | | | [68] |
| Cu | Y | 0.167 | 1.421 | | | | | | | | | 19.80 | 3.97 | 19.80 | 1 | 1 | 1.97 | 0 | 10.4 | 2.8 | 14 | 0 | [56, 74] |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cu | Zr | 0.100 | 1.254 | | | 880 | 1263 | | 0.697 | | | 17.09 | 1.90 | 17.09 | 1 | 0.9 | 0 | 0 | | | | | [75] |
| Cu | Zr | 0.120 | 1.254 | | | 885 | 1285 | | 0.688 | | | 17.09 | 2.33 | 17.09 | 1 | 1 | 0.33 | 0 | | | | | [75] |
| Cu | Zr | 0.250 | 1.254 | | | | | | | | | 16.75 | 5.19 | 15.56 | 1 | 1 | 2 | 1.19 | | | | | [70] |
| Cu | Zr | 0.280 | 1.254 | | 780 | 804 | 1358 | 0.574 | 0.592 | 24 | 0.376 | 16.58 | 5.76 | 14.82 | 1 | 1 | 2 | 1.76 | | | | | [76] |
| Cu | Zr | 0.300 | 1.254 | | | 788 | 1333 | | 0.591 | | | 16.47 | 6.14 | 14.33 | 1 | 1 | 2 | 2.14 | | | | | [64, 75] |
| Cu | Zr | 0.340 | 1.254 | | 762 | 785 | 1263 | 0.603 | 0.622 | 23 | 0.388 | 16.25 | 6.89 | 13.37 | 1 | 1 | 2 | 2.89 | | | | | [77, 78] |
| Cu | Zr | 0.350 | 1.254 | | 781 | 798 | 1248 | 0.626 | 0.639 | 17 | 0.393 | 16.20 | 7.07 | 13.13 | 1 | 1 | 2 | 3.07 | | | | | [75, 79] |
| Cu | Zr | 0.350 | 1.254 | | 745 | 792 | 1279 | 0.582 | 0.619 | 47 | 0.391 | 16.20 | 7.07 | 13.13 | 1 | 1 | 2 | 3.07 | | | | | [76] |
| Cu | Zr | 0.355 | 1.254 | | 747 | 769 | 1243 | 0.601 | 0.618 | 22 | 0.386 | 16.17 | 7.16 | 13.01 | 1 | 1 | 2 | 3.16 | | | | | [80] |
| Cu | Zr | 0.360 | 1.254 | 7.54 | 787 | 833 | 1233 | 0.638 | 0.676 | 46 | 0.412 | 16.15 | 7.25 | 12.89 | 1 | 1 | 2 | 3.25 | | | | | [72, 78] |
| Cu | Zr | 0.380 | 1.254 | | 728 | 793 | 1158 | 0.629 | 0.685 | 65 | 0.421 | 16.04 | 7.62 | 12.43 | 1 | 1 | 2 | 3.62 | | | | | [75] |
| Cu | Zr | 0.382 | 1.254 | | 767 | 823 | 1158 | 0.662 | 0.711 | 56 | 0.428 | 16.03 | 7.65 | 12.38 | 1 | 1 | 2 | 3.65 | | | | | [78] |
| Cu | Zr | 0.400 | 1.254 | | 740 | 760 | 1198 | 0.618 | 0.634 | 20 | 0.392 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | | | | | [36, 64, 81] |
| Cu | Zr | 0.400 | 1.254 | | 714 | 764 | 1198 | 0.596 | 0.638 | 50 | 0.400 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | | | | | [76] |
| Cu | Zr | 0.400 | 1.254 | | 763 | 812 | 1198 | 0.637 | 0.677 | 49 | 0.414 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | | | | | [79] |
| Cu | Zr | 0.400 | 1.254 | | 733 | 791 | 1198 | 0.612 | 0.660 | 58 | 0.410 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | | | | | [66] |
| Cu | Zr | 0.400 | 1.254 | | 755 | 811 | 1198 | 0.630 | 0.677 | 56 | 0.415 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | | | | | [78] |
| Cu | Zr | 0.428 | 1.254 | | | | | | | | | 15.80 | 8.47 | 11.32 | 1 | 1 | 2 | 4.47 | | | | | [64, 70] |
| Dy | Al | 0.400 | 0.806 | | | | | | | | | 10.40 | 5.76 | 8.64 | 1 | 1 | 2 | 1.76 | | | | | [82] |
| Dy | Al | 0.450 | 0.806 | | | | | | | | | 10.54 | 6.54 | 8.00 | 1 | 1 | 2 | 2.54 | | | | | [82] |
| Dy | Al | 0.500 | 0.806 | | | | | | | | | 10.69 | 7.34 | 7.34 | 1 | 1 | 2 | 3.34 | | | | | [82] |
| Dy | Al | 0.550 | 0.806 | | | | | | | | | 10.84 | 8.16 | 6.68 | 1 | 1 | 2 | 4.16 | | | | | [82] |
| Dy | Au | 0.200 | 0.823 | | | | | | | | | 10.28 | 2.57 | 10.28 | 1 | 1 | 0.57 | 0 | | | | | [45] |
| Dy | Cu | 0.300 | 0.72 | | | 540 | | | | | | 9.11 | 3.90 | 9.11 | 1 | 1 | 1.9 | 0 | | | | | [75] |
| Dy | Ni | 0.310 | 0.72 | | | | | | | | | 9.13 | 4.07 | 9.06 | 1 | 1 | 2 | 0.07 | 3 | 10.8 | 4.85 | 12.4 | [56] |
| Er | Au | 0.200 | 0.823 | | | | | | | | | 10.28 | 2.57 | 10.28 | 1 | 1 | 0.57 | 0 | | | | | [45] |
| Er | Cu | 0.300 | 0.72 | | | 566 | | | | | | 9.11 | 3.90 | 9.11 | 1 | 1 | 1.9 | 0 | | | | | [75] |
| Er | Fe | 0.320 | 0.714 | | | | | | | | | 9.10 | 4.19 | 8.90 | 1 | 1 | 2 | 0.19 | | | | | [74] |
| Eu | Au | 0.200 | 0.735 | | | | | | | | | 9.27 | 2.32 | 9.27 | 1 | 1 | 0.32 | 0 | | | | | [45] |
| Fe | B | 0.090 | 0.704 | | | | | | | | | 8.94 | 0.88 | 8.94 | 0.88 | 0 | 0 | 0 | | | | | [83] |
| Fe | B | 0.110 | 0.704 | | | | | | | | | 8.94 | 1.10 | 8.94 | 1 | 0.1 | 0 | 0 | | | | | [83] |
| Fe | B | 0.120 | 0.704 | 7.44 | | 595 | 1573 | | 0.378 | | | 8.94 | 1.22 | 8.94 | 1 | 0.22 | 0 | 0 | | | | | [83] |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe | B | 0.120 | 0.704 | | | 560 | 1573 | | 0.356 | | | 8.94 | 1.22 | 8.94 | 1 | 0.22 | 0 | 0 | | | | | [84] |
| Fe | B | 0.130 | 0.704 | | | 611 | 1548 | | 0.395 | | | 8.94 | 1.34 | 8.94 | 1 | 0.34 | 0 | 0 | | | | | [83] |
| Fe | B | 0.130 | 0.704 | 7.51 | | 770 | 1548 | | 0.497 | | | 8.94 | 1.34 | 8.94 | 1 | 0.34 | 0 | 0 | | | | | [50, 54] |
| Fe | B | 0.130 | 0.704 | | | 585 | 1548 | | 0.378 | | | 8.94 | 1.34 | 8.94 | 1 | 0.34 | 0 | 0 | | | | | [84] |
| Fe | B | 0.140 | 0.704 | | | 623 | 1523 | | 0.409 | | | 8.94 | 1.45 | 8.94 | 1 | 0.45 | 0 | 0 | | | | | [83] |
| Fe | B | 0.140 | 0.704 | 7.5 | | 770 | 1523 | | 0.506 | | | 8.94 | 1.45 | 8.94 | 1 | 0.45 | 0 | 0 | | | | | [54, 79] |
| Fe | B | 0.140 | 0.704 | | | 600 | 1523 | | 0.394 | | | 8.94 | 1.45 | 8.94 | 1 | 0.45 | 0 | 0 | | | | | [84] |
| Fe | B | 0.150 | 0.704 | | | 641 | 1493 | | 0.429 | | | 8.94 | 1.58 | 8.94 | 1 | 0.58 | 0 | 0 | | | | | [83] |
| Fe | B | 0.150 | 0.704 | | | 750 | 1493 | | 0.502 | | | 8.94 | 1.58 | 8.94 | 1 | 0.58 | 0 | 0 | | | | | [54, 83, 85] |
| Fe | B | 0.160 | 0.704 | | | 653 | 1478 | | 0.442 | | | 8.94 | 1.70 | 8.94 | 1 | 0.7 | 0 | 0 | | | | | [83] |
| Fe | B | 0.160 | 0.704 | 7.51 | | 740 | 1478 | | 0.501 | | | 8.94 | 1.70 | 8.94 | 1 | 0.7 | 0 | 0 | | | | | [54, 83] |
| Fe | B | 0.160 | 0.704 | 7.38 | | 643 | 1478 | | 0.435 | | | 8.94 | 1.70 | 8.94 | 1 | 0.7 | 0 | 0 | | | | | [48, 84] |
| Fe | B | 0.170 | 0.704 | | | 666 | 1447 | | 0.460 | | | 8.94 | 1.83 | 8.94 | 1 | 0.83 | 0 | 0 | | | | | [83] |
| Fe | B | 0.170 | 0.704 | 7.47 | | 740 | 1447 | | 0.511 | | | 8.94 | 1.83 | 8.94 | 1 | 0.83 | 0 | 0 | | | | | [54] |
| Fe | B | 0.170 | 0.704 | | | 710 | 1447 | | 0.491 | | | 8.94 | 1.83 | 8.94 | 1 | 0.83 | 0 | 0 | | | | | [36] |
| Fe | B | 0.180 | 0.704 | | | 678 | 1468 | | 0.462 | | | 8.94 | 1.96 | 8.94 | 1 | 0.96 | 0 | 0 | | | | | [83] |
| Fe | B | 0.180 | 0.704 | 7.48 | | 738 | 1468 | | 0.503 | | | 8.94 | 1.96 | 8.94 | 1 | 0.96 | 0 | 0 | | | | | [50, 54] |
| Fe | B | 0.180 | 0.704 | | | 657 | 1468 | | 0.448 | | | 8.94 | 1.96 | 8.94 | 1 | 0.96 | 0 | 0 | | | | | [84] |
| Fe | B | 0.190 | 0.704 | | | 687 | 1493 | | 0.460 | | | 8.94 | 2.10 | 8.94 | 1 | 1 | 0.1 | 0 | | | | | [83] |
| Fe | B | 0.190 | 0.704 | 7.5 | | 740 | 1493 | | 0.496 | | | 8.94 | 2.10 | 8.94 | 1 | 1 | 0.1 | 0 | | | | | [54] |
| Fe | B | 0.190 | 0.704 | | | 698 | 1493 | | 0.468 | | | 8.94 | 2.10 | 8.94 | 1 | 1 | 0.1 | 0 | | | | | [49] |
| Fe | B | 0.200 | 0.704 | | | 694 | 1523 | | 0.456 | | | 8.94 | 2.23 | 8.94 | 1 | 1 | 0.23 | 0 | 0 | 8.64 | 2.16 | 12.4 | [56, 83] |
| Fe | B | 0.200 | 0.704 | 7.4 | | 700 | 1523 | | 0.460 | | | 8.94 | 2.23 | 8.94 | 1 | 1 | 0.23 | 0 | | | | | [72, 86, 87] |
| Fe | B | 0.200 | 0.704 | 7.45 | | 738 | 1523 | | 0.485 | | | 8.94 | 2.23 | 8.94 | 1 | 1 | 0.23 | 0 | | | | | [54] |
| Fe | B | 0.200 | 0.704 | | | 650 | 1523 | | 0.427 | | | 8.94 | 2.23 | 8.94 | 1 | 1 | 0.23 | 0 | | | | | [48, 84] |
| Fe | B | 0.210 | 0.704 | | | 701 | 1538 | | 0.456 | | | 8.94 | 2.38 | 8.94 | 1 | 1 | 0.38 | 0 | | | | | [83] |
| Fe | B | 0.210 | 0.704 | 7.41 | | 728 | 1538 | | 0.473 | | | 8.94 | 2.38 | 8.94 | 1 | 1 | 0.38 | 0 | | | | | [54] |
| Fe | B | 0.210 | 0.704 | | | 703 | 1493 | | 0.471 | | | 8.94 | 2.38 | 8.94 | 1 | 1 | 0.38 | 0 | | | | | [49] |
| Fe | B | 0.220 | 0.704 | 7.38 | | 720 | 1558 | | 0.462 | | | 8.94 | 2.52 | 8.94 | 1 | 1 | 0.52 | 0 | | | | | [50, 54] |
| Fe | B | 0.220 | 0.704 | | | 665 | 1558 | | 0.427 | | | 8.94 | 2.52 | 8.94 | 1 | 1 | 0.52 | 0 | | | | | [84] |
| Fe | B | 0.230 | 0.704 | 7.34 | | 730 | 1583 | | 0.461 | | | 8.94 | 2.67 | 8.94 | 1 | 1 | 0.67 | 0 | | | | | [54] |
| Fe | B | 0.240 | 0.704 | 7.3 | | 732 | 1593 | | 0.460 | | | 8.94 | 2.82 | 8.94 | 1 | 1 | 0.82 | 0 | | | | | [54] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe | B | 0.240 | 0.704 | | | 677 | 1593 | | 0.425 | | | 8.94 | 2.82 | 8.94 | 1 | 1 | 0.82 | 0 | | | | | [84] |
| Fe | B | 0.250 | 0.704 | 7.27 | | | | | | | | 8.94 | 2.98 | 8.94 | 1 | 1 | 0.98 | 0 | | | | | [54, 87] |
| Fe | B | 0.250 | 0.704 | 7.22 | | | | | | | | 8.94 | 2.98 | 8.94 | 1 | 1 | 0.98 | 0 | | | | | [48] |
| Fe | B | 0.260 | 0.704 | 7.215 | | 734 | 1618 | | 0.454 | | | 8.94 | 3.14 | 8.94 | 1 | 1 | 1.14 | 0 | | | | | [54] |
| Fe | B | 0.260 | 0.704 | | | 685 | 1618 | | 0.423 | | | 8.94 | 3.14 | 8.94 | 1 | 1 | 1.14 | 0 | | | | | [84] |
| Fe | B | 0.270 | 0.704 | 7.18 | | | | | | | | 8.94 | 3.30 | 8.94 | 1 | 1 | 1.3 | 0 | | | | | [54] |
| Fe | B | 0.280 | 0.704 | 7.09 | | | | | | | | 8.94 | 3.47 | 8.94 | 1 | 1 | 1.47 | 0 | | | | | [84] |
| Fe | C | 0.155 | 0.616 | | | | | | | | | 7.99 | 1.47 | 7.99 | 1 | 0.47 | 0 | 0 | | | | | [12] |
| Fe | Hf | 0.090 | 1.264 | | | | | | | | | 17.25 | 1.71 | 17.25 | 1 | 0.71 | 0 | 0 | | | | | [12] |
| Fe | Nd | 0.150 | 1.424 | | | | | | | | | 19.85 | 3.50 | 19.85 | 1 | 1 | 1.5 | 0 | | | | | [79] |
| Fe | Nd | 0.180 | 1.424 | | | | | | | | | 19.72 | 4.27 | 19.45 | 1 | 1 | 2 | 0.27 | | | | | [79] |
| Fe | Nd | 0.210 | 1.424 | | | | | | | | | 19.39 | 4.91 | 18.48 | 1 | 1 | 2 | 0.91 | | | | | [79] |
| Fe | Nd | 0.250 | 1.424 | | | | | | | | | 18.97 | 5.74 | 17.22 | 1 | 1 | 2 | 1.74 | | | | | [79] |
| Fe | P | 0.145 | 0.816 | 7.285 | | | | | | | | 10.20 | 1.73 | 10.20 | 1 | 0.73 | 0 | 0 | | | | | [47] |
| Fe | P | 0.145 | 0.816 | 7.25 | | | | | | | | 10.20 | 1.73 | 10.20 | 1 | 0.73 | 0 | 0 | | | | | [54] |
| Fe | P | 0.150 | 0.816 | | | | | | | | | 10.20 | 1.80 | 10.20 | 1 | 0.8 | 0 | 0 | | | | | [88] |
| Fe | P | 0.160 | 0.816 | 7.27 | | | | | | | | 10.20 | 1.94 | 10.20 | 1 | 0.94 | 0 | 0 | | | | | [47] |
| Fe | P | 0.160 | 0.816 | 7.2 | | | | | | | | 10.20 | 1.94 | 10.20 | 1 | 0.94 | 0 | 0 | | | | | [54] |
| Fe | P | 0.170 | 0.816 | 7.26 | | 640 | 1321 | | 0.484 | | | 10.20 | 2.09 | 10.20 | 1 | 1 | 0.09 | 0 | | | | | [47, 86, 88] |
| Fe | P | 0.180 | 0.816 | 7.225 | | | | | | | | 10.20 | 2.24 | 10.20 | 1 | 1 | 0.24 | 0 | | | | | [47, 88] |
| Fe | P | 0.182 | 0.816 | 7.14 | | | | | | | | 10.20 | 2.27 | 10.20 | 1 | 1 | 0.27 | 0 | | | | | [54] |
| Fe | P | 0.190 | 0.816 | 7.175 | | | | | | | | 10.20 | 2.39 | 10.20 | 1 | 1 | 0.39 | 0 | | | | | [47] |
| Fe | P | 0.200 | 0.816 | 7.118 | | | | | | | | 10.20 | 2.55 | 10.20 | 1 | 1 | 0.55 | 0 | | | | | [47, 88] |
| Fe | P | 0.200 | 0.816 | 7.1 | | | | | | | | 10.20 | 2.55 | 10.20 | 1 | 1 | 0.55 | 0 | | | | | [54] |
| Fe | P | 0.216 | 0.816 | 7.03 | | | | | | | | 10.20 | 2.81 | 10.20 | 1 | 1 | 0.81 | 0 | | | | | [54] |
| Fe | P | 0.240 | 0.816 | | | | | | | | | 10.20 | 3.22 | 10.20 | 1 | 1 | 1.22 | 0 | | | | | [88] |
| Fe | P | 0.250 | 0.816 | | | | | | | | | 10.20 | 3.40 | 10.20 | 1 | 1 | 1.4 | 0 | 3.5 | 8.1 | 2.6 | 10.4 | [88] |
| Fe | P | 0.260 | 0.816 | | | | | | | | | 10.20 | 3.58 | 10.20 | 1 | 1 | 1.58 | 0 | | | | | [88] |
| Fe | Sc | 0.100 | 1.296 | | | | | | | | | 17.76 | 1.97 | 17.76 | 1 | 0.97 | 0 | 0 | | | | | [89] |
| Fe | Si | 0.250 | 0.88 | | | | | | | | | 10.95 | 3.65 | 10.95 | 1 | 1 | 1.65 | 0 | | | | | [87] |
| Fe | Th | 0.280 | 1.424 | | | 813 | 1523 | | 0.534 | | | 18.66 | 6.34 | 16.31 | 1 | 1 | 2 | 2.34 | | | | | [90] |
| Fe | Th | 0.300 | 1.424 | | | 808 | 1458 | | 0.554 | | | 18.46 | 6.74 | 15.72 | 1 | 1 | 2 | 2.74 | | | | | [90] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe | Th | 0.310 | 1.424 | | | 745 | 1383 | | 0.539 | | | 18.36 | 6.93 | 15.43 | 1 | 1 | 2 | 2.93 | | | | | [90] |
| Fe | Th | 0.330 | 1.424 | | | 745 | 1383 | | 0.539 | | | 18.17 | 7.32 | 14.85 | 1 | 1 | 2 | 3.32 | | | | | [90, 91] |
| Fe | Th | 0.395 | 1.424 | | | | | | | | | 17.56 | 8.52 | 13.05 | 1 | 1 | 2 | 4.52 | | | | | [90, 91] |
| Fe | Zr | 0.080 | 1.264 | | | | | | | | | 17.25 | 1.50 | 17.25 | 1 | 0.5 | 0 | 0 | | | | | [92] |
| Fe | Zr | 0.090 | 1.264 | | | 774 | 1653 | | 0.468 | | | 17.25 | 1.71 | 17.25 | 1 | 0.71 | 0 | 0 | | | | | [58, 93, 94] |
| Fe | Zr | 0.100 | 1.264 | | | 775 | 1610 | | 0.481 | | | 17.25 | 1.92 | 17.25 | 1 | 0.92 | 0 | 0 | | | | | [58, 92, 93] |
| Fe | Zr | 0.100 | 1.264 | | | 791 | 1610 | | 0.491 | | | 17.25 | 1.92 | 17.25 | 1 | 0.92 | 0 | 0 | | | | | [61, 62, 95] |
| Fe | Zr | 0.110 | 1.264 | | | 770 | 1673 | | 0.460 | | | 17.25 | 2.13 | 17.25 | 1 | 1 | 0.13 | 0 | | | | | [58, 93] |
| Fe | Zr | 0.120 | 1.264 | | | | | | | | | 17.25 | 2.35 | 17.25 | 1 | 1 | 0.35 | 0 | | | | | [92, 93] |
| Gd | Ag | 0.300 | 0.818 | | | | | | | | | 10.27 | 4.28 | 9.99 | 1 | 1 | 2 | 0.28 | | | | | [96, 97] |
| Gd | Ag | 0.460 | 0.818 | | | | | | | | | 10.70 | 6.76 | 7.94 | 1 | 1 | 2 | 2.76 | | | | | [96] |
| Gd | Al | 0.220 | 0.801 | | | 591 | 1173 | | 0.504 | | | 10.03 | 2.83 | 10.03 | 1 | 1 | 0.83 | 0 | | | | | [96-98] |
| Gd | Al | 0.400 | 0.801 | | | | | | | | | 10.35 | 5.74 | 8.61 | 1 | 1 | 2 | 1.74 | | | | | [82] |
| Gd | Al | 0.450 | 0.801 | | | | | | | | | 10.49 | 6.52 | 7.97 | 1 | 1 | 2 | 2.52 | | | | | [82] |
| Gd | Al | 0.500 | 0.801 | | | | | | | | | 10.64 | 7.32 | 7.32 | 1 | 1 | 2 | 3.32 | | | | | [82] |
| Gd | Al | 0.550 | 0.801 | | | | | | | | | 10.80 | 8.14 | 6.66 | 1 | 1 | 2 | 4.14 | | | | | [82] |
| Gd | Au | 0.200 | 0.818 | | | | | | | | | 10.22 | 2.56 | 10.22 | 1 | 1 | 0.56 | 0 | | | | | [45, 96, 97] |
| Gd | Au | 0.250 | 0.818 | | | | | | | | | 10.22 | 3.41 | 10.22 | 1 | 1 | 1.41 | 0 | | | | | [99] |
| Gd | C | 0.200 | 0.438 | | | | | | | | | 6.22 | 1.55 | 6.22 | 1 | 0.55 | 0 | 0 | | | | | [97] |
| Gd | Co | 0.310 | 0.71 | | | 550 | 1033 | | 0.532 | | | 9.01 | 4.03 | 8.98 | 1 | 1 | 2 | 0.03 | | | | | [98] |
| Gd | Co | 0.400 | 0.71 | | | | | | | | | 9.34 | 5.34 | 8.01 | 1 | 1 | 2 | 1.34 | | | | | [100] |
| Gd | Co | 0.450 | 0.71 | | | 590 | 1153 | | 0.512 | | | 9.54 | 6.09 | 7.45 | 1 | 1 | 2 | 2.09 | | | | | [98, 100] |
| Gd | Co | 0.500 | 0.71 | | | 600 | 1273 | | 0.471 | | | 9.74 | 6.87 | 6.87 | 1 | 1 | 2 | 2.87 | | | | | [100] |
| Gd | Co | 0.550 | 0.71 | | | 575 | 1353 | | 0.425 | | | 9.96 | 7.68 | 6.28 | 1 | 1 | 2 | 3.68 | | | | | [98] |
| Gd | Cu | 0.240 | 0.716 | | | 473 | 1073 | | 0.441 | | | 9.07 | 2.86 | 9.07 | 1 | 1 | 0.86 | 0 | | | | | [98] |
| Gd | Cu | 0.300 | 0.716 | | | 470 | 948 | | 0.496 | | | 9.07 | 3.89 | 9.07 | 1 | 1 | 1.89 | 0 | | | | | [96-98] |
| Gd | Cu | 0.340 | 0.716 | | | 473 | 1025 | | 0.461 | | | 9.19 | 4.48 | 8.70 | 1 | 1 | 2 | 0.48 | | | | | [98] |
| Gd | Cu | 0.580 | 0.716 | | | | | | | | | 10.14 | 8.20 | 5.94 | 1 | 1 | 2 | 4.2 | | | | | [75] |
| Gd | Fe | 0.320 | 0.71 | | | | | | | | | 9.05 | 4.18 | 8.87 | 1 | 1 | 2 | 0.18 | | | | | [98] |
| Gd | Fe | 0.400 | 0.71 | | | 413 | 1223 | | 0.338 | | | 9.34 | 5.34 | 8.01 | 1 | 1 | 2 | 1.34 | | | | | [98] |
| Gd | Fe | 0.500 | 0.71 | | | | | | | | | 9.74 | 6.87 | 6.87 | 1 | 1 | 2 | 2.87 | | | | | [98] |
| Gd | Ga | 0.210 | 0.761 | | | 558 | 1153 | | 0.484 | | | 9.57 | 2.54 | 9.57 | 1 | 1 | 0.54 | 0 | | | | | [96-98] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gd | Ga | 0.250 | 0.761 | | | | | | | | | 9.57 | 3.19 | 9.57 | 1 | 1 | 1.19 | 0 | | | | | [98] |
| Gd | Mn | 0.400 | 0.75 | | | 520 | 1153 | | 0.451 | | | 9.79 | 5.51 | 8.27 | 1 | 1 | 2 | 1.51 | | | | | [98] |
| Gd | Ni | 0.310 | 0.716 | | | 553 | 953 | | 0.580 | | | 9.08 | 4.05 | 9.02 | 1 | 1 | 2 | 0.05 | | | | | [97, 98] |
| Gd | Ni | 0.320 | 0.716 | | | | | | | | | 9.11 | 4.20 | 8.92 | 1 | 1 | 2 | 0.2 | | | | | [96] |
| Gd | Ni | 0.400 | 0.716 | | | 538 | 903 | | 0.596 | | | 9.41 | 5.36 | 8.04 | 1 | 1 | 2 | 1.36 | | | | | [98] |
| Gd | Pd | 0.240 | 0.807 | | | 569 | 1058 | | 0.538 | | | 10.09 | 3.19 | 10.09 | 1 | 1 | 1.19 | 0 | | | | | [96-98] |
| Gd | Pt | 0.170 | 0.79 | | | 628 | 1393 | | 0.451 | | | 9.90 | 2.03 | 9.90 | 1 | 1 | 0.03 | 0 | | | | | [98] |
| Gd | Rh | 0.180 | 0.75 | | | 563 | 1218 | | 0.462 | | | 9.44 | 2.07 | 9.44 | 1 | 1 | 0.07 | 0 | | | | | [96-98] |
| Gd | Ru | 0.150 | 0.761 | | | 573 | 1190 | | 0.482 | | | 9.57 | 1.69 | 9.57 | 1 | 0.69 | 0 | 0 | | | | | [98] |
| Gd | Ru | 0.300 | 0.761 | | | 728 | 1288 | | 0.565 | | | 9.59 | 4.08 | 9.51 | 1 | 1 | 2 | 0.08 | | | | | [98] |
| Gd | Ru | 0.400 | 0.761 | | | 765 | 1528 | | 0.501 | | | 9.91 | 5.56 | 8.35 | 1 | 1 | 2 | 1.56 | | | | | [98] |
| Hf | Au | 0.300 | 0.911 | | | 1000 | 1793 | | 0.558 | | | 12.20 | 4.86 | 11.34 | 1 | 1 | 2 | 0.86 | | | | | [101] |
| Hf | Co | 0.220 | 0.791 | | | 758 | 1833 | | 0.414 | | | 9.91 | 2.80 | 9.91 | 1 | 1 | 0.8 | 0 | | | | | [102] |
| Hf | Co | 0.330 | 0.791 | | | | | | | | | 10.03 | 4.63 | 9.40 | 1 | 1 | 2 | 0.63 | | | | | [103] |
| Hf | Co | 0.400 | 0.791 | | | 823 | 1913 | | 0.430 | | | 10.24 | 5.70 | 8.54 | 1 | 1 | 2 | 1.7 | | | | | [102] |
| Hf | Cu | 0.290 | 0.797 | | | | | | | | | 9.99 | 4.06 | 9.94 | 1 | 1 | 2 | 0.06 | | | | | [64] |
| Hf | Cu | 0.300 | 0.797 | | | 739 | 1333 | | 0.554 | | | 10.02 | 4.21 | 9.82 | 1 | 1 | 2 | 0.21 | | | | | [64, 75] |
| Hf | Cu | 0.400 | 0.797 | | | | | | | | | 10.31 | 5.72 | 8.58 | 1 | 1 | 2 | 1.72 | | | | | [64] |
| Hf | Cu | 0.500 | 0.797 | | | | | | | | | 10.61 | 7.30 | 7.30 | 1 | 1 | 2 | 3.3 | | | | | [64] |
| Hf | Cu | 0.550 | 0.797 | | 771 | 830 | 1295 | 0.595 | 0.641 | 59 | 0.402 | 10.77 | 8.12 | 6.65 | 1 | 1 | 2 | 4.12 | | | | | [66] |
| Hf | Cu | 0.560 | 0.797 | | | 831 | 1523 | | 0.546 | | | 10.80 | 8.29 | 6.51 | 1 | 1 | 2 | 4.29 | | | | | [75] |
| Hf | Cu | 0.570 | 0.797 | | | | | | | | | 10.83 | 8.45 | 6.38 | 1 | 1 | 2 | 4.45 | | | | | [73] |
| Hf | Cu | 0.571 | 0.797 | | | | | | | | | 10.83 | 8.47 | 6.36 | 1 | 1 | 2 | 4.47 | | | | | [64] |
| Hf | Ge | 0.130 | 0.722 | | | | | | | | | 9.13 | 1.36 | 9.13 | 1 | 0.36 | 0 | 0 | | | | | [104, 105] |
| Hf | Ge | 0.150 | 0.722 | | | | | | | | | 9.13 | 1.61 | 9.13 | 1 | 0.61 | 0 | 0 | | | | | [104, 105] |
| Hf | Ni | 0.200 | 0.797 | | | 738 | 1533 | | 0.481 | | | 9.98 | 2.50 | 9.98 | 1 | 1 | 0.5 | 0 | | | | | [102] |
| Hf | Ni | 0.250 | 0.797 | | | 753 | 1613 | | 0.467 | | | 9.98 | 3.33 | 9.98 | 1 | 1 | 1.33 | 0 | | | | | [102] |
| Hf | Ni | 0.300 | 0.797 | | | | | | | | | 10.02 | 4.21 | 9.82 | 1 | 1 | 2 | 0.21 | | | | | [64] |
| Hf | Ni | 0.330 | 0.797 | | | | | | | | | 10.11 | 4.65 | 9.45 | 1 | 1 | 2 | 0.65 | | | | | [103] |
| Hf | Ni | 0.380 | 0.797 | | | 808 | 1753 | | 0.461 | | | 10.25 | 5.41 | 8.83 | 1 | 1 | 2 | 1.41 | | | | | [102] |
| Hf | Ni | 0.400 | 0.797 | | | | | | | | | 10.31 | 5.72 | 8.58 | 1 | 1 | 2 | 1.72 | | | | | [64] |
| Hf | Ni | 0.500 | 0.797 | | | | | | | | | 10.61 | 7.30 | 7.30 | 1 | 1 | 2 | 3.3 | | | | | [64] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hf | Ni | 0.571 | 0.797 | | | | | | | | | 10.83 | 8.47 | 6.36 | 1 | 1 | 2 | 4.47 | | | | | [64] |
| Hf | Si | 0.130 | 0.696 | | | | | | | | | 8.85 | 1.32 | 8.85 | 1 | 0.32 | 0 | 0 | | | | | [104, 105] |
| Hf | Si | 0.150 | 0.696 | | | | | | | | | 8.85 | 1.56 | 8.85 | 1 | 0.56 | 0 | 0 | | | | | [104, 105] |
| Hf | Si | 0.170 | 0.696 | | | | | | | | | 8.85 | 1.81 | 8.85 | 1 | 0.81 | 0 | 0 | | | | | [104, 105] |
| Ho | Au | 0.200 | 0.814 | | | | | | | | | 10.17 | 2.54 | 10.17 | 1 | 1 | 0.54 | 0 | | | | | [45] |
| La | Ag | 0.250 | 0.77 | | | | | | | | | 9.67 | 3.22 | 9.67 | 1 | 1 | 1.22 | 0 | | | | | [106] |
| La | Ag | 0.260 | 0.77 | | | | | | | | | 9.67 | 3.40 | 9.67 | 1 | 1 | 1.4 | 0 | | | | | [107] |
| La | Ag | 0.300 | 0.77 | | | 363 | 913 | | 0.398 | | | 9.69 | 4.11 | 9.59 | 1 | 1 | 2 | 0.11 | | | | | [107] |
| La | Ag | 0.400 | 0.77 | | | | | | | | | 10.01 | 5.60 | 8.40 | 1 | 1 | 2 | 1.6 | | | | | [107] |
| La | Ag | 0.560 | 0.77 | | | 363 | 1098 | | 0.331 | | | 10.56 | 8.15 | 6.40 | 1 | 1 | 2 | 4.15 | | | | | [107] |
| La | Al | 0.130 | 0.754 | | | | | | | | | 9.49 | 1.42 | 9.49 | 1 | 0.42 | 0 | 0 | | | | | [30] |
| La | Al | 0.180 | 0.754 | | | | | | | | | 9.49 | 2.08 | 9.49 | 1 | 1 | 0.08 | 0 | | | | | [108] |
| La | Al | 0.200 | 0.754 | | | | | | | | | 9.49 | 2.37 | 9.49 | 1 | 1 | 0.37 | 0 | | | | | [31, 108] |
| La | Al | 0.220 | 0.754 | | | 500 | 848 | | 0.590 | | | 9.49 | 2.68 | 9.49 | 1 | 1 | 0.68 | 0 | | | | | [30, 108] |
| La | Al | 0.250 | 0.754 | | | | | | | | | 9.49 | 3.16 | 9.49 | 1 | 1 | 1.16 | 0 | | | | | [108] |
| La | Al | 0.270 | 0.754 | | | | | | | | | 9.49 | 3.51 | 9.49 | 1 | 1 | 1.51 | 0 | | | | | [108] |
| La | Al | 0.300 | 0.754 | | | 520 | 955 | | 0.545 | | | 9.50 | 4.05 | 9.45 | 1 | 1 | 2 | 0.05 | | | | | [31, 108] |
| La | Al | 0.320 | 0.754 | | | | | | | | | 9.56 | 4.34 | 9.22 | 1 | 1 | 2 | 0.34 | | | | | [108] |
| La | Al | 0.340 | 0.754 | | | 540 | 1023 | | 0.528 | | | 9.63 | 4.63 | 9.00 | 1 | 1 | 2 | 0.63 | | | | | [30, 108] |
| La | Al | 0.360 | 0.754 | | | 560 | 1058 | | 0.529 | | | 9.70 | 4.93 | 8.77 | 1 | 1 | 2 | 0.93 | | | | | [30] |
| La | Al | 0.400 | 0.754 | | | 580 | 1113 | | 0.521 | | | 9.83 | 5.53 | 8.30 | 1 | 1 | 2 | 1.53 | | | | | [30, 31] |
| La | Al | 0.500 | 0.754 | | | 620 | 1413 | | 0.439 | | | 10.18 | 7.09 | 7.09 | 1 | 1 | 2 | 3.09 | | | | | [30, 31] |
| La | Al | 0.550 | 0.754 | | | | | | | | | 10.37 | 7.90 | 6.47 | 1 | 1 | 2 | 3.9 | | | | | [30] |
| La | Al | 0.585 | 0.754 | | | | | | | | | 10.51 | 8.49 | 6.02 | 1 | 1 | 2 | 4.49 | | | | | [30] |
| La | Au | 0.180 | 0.77 | | | | | | | | | 9.67 | 2.12 | 9.67 | 1 | 1 | 0.12 | 0 | | | | | [108, 109] |
| La | Au | 0.200 | 0.77 | | | | | | | | | 9.67 | 2.42 | 9.67 | 1 | 1 | 0.42 | 0 | | | | | [108, 109] |
| La | Au | 0.220 | 0.77 | | | | | | | | | 9.67 | 2.73 | 9.67 | 1 | 1 | 0.73 | 0 | | | | | [109] |
| La | Au | 0.240 | 0.77 | | | | | | | | | 9.67 | 3.05 | 9.67 | 1 | 1 | 1.05 | 0 | | | | | [108-110] |
| La | Au | 0.250 | 0.77 | | | | | | | | | 9.67 | 3.22 | 9.67 | 1 | 1 | 1.22 | 0 | | | | | [108] |
| La | Au | 0.260 | 0.77 | | | | | | | | | 9.67 | 3.40 | 9.67 | 1 | 1 | 1.4 | 0 | | | | | [109] |
| La | Au | 0.270 | 0.77 | | | | | | | | | 9.67 | 3.58 | 9.67 | 1 | 1 | 1.58 | 0 | | | | | [108] |
| La | Cu | 0.270 | 0.674 | | | | | | | | | 8.61 | 3.18 | 8.61 | 1 | 1 | 1.18 | 0 | | | | | [111] |

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| La | Cu | 0.300 | 0.674 | | | 395 | 773 | | 0.511 | | | 8.61 | 3.69 | 8.61 | 1 | 1 | 1.69 | 0 | | | | [31, 75] |
| La | Cu | 0.370 | 0.674 | | | | | | | | | 8.81 | 4.74 | 8.07 | 1 | 1 | 2 | 0.74 | | | | [111] |
| La | Cu | 0.375 | 0.674 | | | | | | | | | 8.83 | 4.81 | 8.02 | 1 | 1 | 2 | 0.81 | | | | [111] |
| La | Ga | 0.160 | 0.717 | 6.07 | | | | | | | | 9.07 | 1.73 | 9.07 | 1 | 0.73 | 0 | 0 | | | | [112] |
| La | Ga | 0.180 | 0.717 | 6.24 | | | | | | | | 9.07 | 1.99 | 9.07 | 1 | 0.99 | 0 | 0 | | | | [112] |
| La | Ga | 0.200 | 0.717 | 6.25 | | | | | | | | 9.07 | 2.27 | 9.07 | 1 | 1 | 0.27 | 0 | | | | [112] |
| La | Ga | 0.220 | 0.717 | 6.28 | | | | | | | | 9.07 | 2.56 | 9.07 | 1 | 1 | 0.56 | 0 | | | | [112] |
| La | Ga | 0.240 | 0.717 | 6.22 | | | | | | | | 9.07 | 2.87 | 9.07 | 1 | 1 | 0.87 | 0 | | | | [112] |
| La | Ga | 0.260 | 0.717 | 6.28 | | | | | | | | 9.07 | 3.19 | 9.07 | 1 | 1 | 1.19 | 0 | | | | [112] |
| La | Ga | 0.280 | 0.717 | 6.42 | | | | | | | | 9.07 | 3.53 | 9.07 | 1 | 1 | 1.53 | 0 | | | | [112] |
| La | Ge | 0.170 | 0.61 | | | | | | | | | 7.93 | 1.62 | 7.93 | 1 | 0.62 | 0 | 0 | | | | [108] |
| La | Ge | 0.200 | 0.61 | | | | | | | | | 7.93 | 1.98 | 7.93 | 1 | 0.98 | 0 | 0 | | | | [108] |
| La | Ge | 0.220 | 0.61 | | | | | | | | | 7.93 | 2.24 | 7.93 | 1 | 1 | 0.24 | 0 | | | | [108] |
| La | Ni | 0.200 | 0.674 | | | | | | | | | 8.61 | 2.15 | 8.61 | 1 | 1 | 0.15 | 0 | | | | [30] |
| La | Ni | 0.300 | 0.674 | | | 465 | 1433 | | 0.324 | | | 8.61 | 3.69 | 8.61 | 1 | 1 | 1.69 | 0 | | | | [30] |
| La | Ni | 0.400 | 0.674 | | | 495 | 1033 | | 0.479 | | | 8.93 | 5.17 | 7.76 | 1 | 1 | 2 | 1.17 | | | | [30, 113] |
| La | Ni | 0.480 | 0.674 | | | 515 | 958 | | 0.538 | | | 9.28 | 6.37 | 6.90 | 1 | 1 | 2 | 2.37 | | | | [30] |
| Mg | Cu | 0.200 | 0.788 | | | 405 | 813 | | 0.498 | | | 9.87 | 2.47 | 9.87 | 1 | 1 | 0.47 | 0 | | | | [114-116] |
| Mg | Cu | 0.300 | 0.788 | | | 420 | 833 | | 0.504 | | | 9.90 | 4.17 | 9.73 | 1 | 1 | 2 | 0.17 | | | | [114-116] |
| Mg | Cu | 0.400 | 0.788 | | | 473 | 823 | | 0.575 | | | 10.20 | 5.68 | 8.52 | 1 | 1 | 2 | 1.68 | | | | [114-116] |
| Mg | Ga | 0.187 | 0.838 | | | | | | | | | 10.45 | 2.41 | 10.45 | 1 | 1 | 0.41 | 0 | | | | [117] |
| Mg | Ni | 0.100 | 0.788 | | | | | | | | | 9.87 | 1.10 | 9.87 | 1 | 0.1 | 0 | 0 | | | | [114, 118] |
| Mg | Ni | 0.150 | 0.788 | | | | | | | | | 9.87 | 1.74 | 9.87 | 1 | 0.74 | 0 | 0 | | | | [114, 118] |
| Mg | Ni | 0.200 | 0.788 | | | 438 | 973 | | 0.450 | | | 9.87 | 2.47 | 9.87 | 1 | 1 | 0.47 | 0 | | | | [115, 116, 118] |
| Mg | Y | 0.150 | 1.119 | | | | | | | | | 15.04 | 2.65 | 15.04 | 1 | 1 | 0.65 | 0 | | | | [114, 119] |
| Mg | Y | 0.160 | 1.119 | | | | | | | | | 15.04 | 2.86 | 15.04 | 1 | 1 | 0.86 | 0 | | | | [115] |
| Mg | Zn | 0.250 | 0.863 | | | | | | | | | 10.74 | 3.58 | 10.74 | 1 | 1 | 1.58 | 0 | | | | [40, 120] |
| Mg | Zn | 0.281 | 0.863 | | | | | | | | | 10.76 | 4.15 | 10.61 | 1 | 1 | 2 | 0.15 | | | | [121] |
| Mg | Zn | 0.292 | 0.863 | | | | | | | | | 10.78 | 4.32 | 10.47 | 1 | 1 | 2 | 0.32 | | | | [121] |
| Mg | Zn | 0.300 | 0.863 | | | | | | | | | 10.80 | 4.44 | 10.36 | 1 | 1 | 2 | 0.44 | | | | [120] |
| Mg | Zn | 0.321 | 0.863 | | | | | | | | | 10.84 | 4.76 | 10.08 | 1 | 1 | 2 | 0.76 | | | | [121] |
| Mg | Zn | 0.350 | 0.863 | | 390 | | 616 | 0.633 | | | | 10.90 | 5.22 | 9.69 | 1 | 1 | 2 | 1.22 | | | | [40] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mg | Zn | 0.350 | 0.863 | | 359 | 379 | 616 | 0.583 | 0.615 | 20 | 0.389 | 10.90 | 5.22 | 9.69 | 1 | 1 | 2 | 1.22 | | | | | [120, 122] |
| Mg | Zn | 0.400 | 0.863 | | | | | | | | | 11.01 | 6.00 | 9.00 | 1 | 1 | 2 | 2 | | | | | [120] |
| Mn | Si | 0.230 | 0.833 | | | | | | | | | 10.40 | 3.11 | 10.40 | 1 | 1 | 1.11 | 0 | | | | | [12] |
| Mn | Zr | 0.100 | 1.197 | | | | | | | | | 16.21 | 1.80 | 16.21 | 1 | 0.8 | 0 | 0 | | | | | [123] |
| Mo | Zr | 0.400 | 1.137 | | | | | | | | | 14.77 | 7.51 | 11.26 | 1 | 1 | 2 | 3.51 | | | | | [124] |
| Mo | Zr | 0.450 | 1.137 | | | | | | | | | 14.64 | 8.39 | 10.25 | 1 | 1 | 2 | 4.39 | | | | | [124] |
| Mo | Zr | 0.466 | 1.137 | | | | | | | | | 14.60 | 8.67 | 9.93 | 1 | 1 | 2 | 4.67 | | | | | [124] |
| Nb | Ir | 0.450 | 0.951 | | | 1133 | 2373 | | 0.477 | | | 12.84 | 7.58 | 9.26 | 1 | 1 | 2 | 3.58 | | | | | [125] |
| Nb | Ir | 0.500 | 0.951 | | | | | | | | | 12.88 | 8.44 | 8.44 | 1 | 1 | 2 | 4.44 | | | | | [125] |
| Nb | Ni | 0.400 | 0.881 | 8.86 | | | | | | | | 12.01 | 6.40 | 9.60 | 1 | 1 | 2 | 2.4 | 3.8 | 8.2 | 5.5 | 9 | [56, 74, 110] |
| Nb | Ni | 0.500 | 0.881 | 8.91 | | 961 | 1560 | | 0.616 | | | 12.21 | 8.10 | 8.10 | 1 | 1 | 2 | 4.1 | 5 | 7.4 | 7.4 | 7.5 | [56, 74, 126, 127] |
| Nb | Rh | 0.400 | 0.923 | | | | | | | | | 12.48 | 6.59 | 9.89 | 1 | 1 | 2 | 2.59 | | | | | [125] |
| Nb | Rh | 0.420 | 0.923 | | | | | | | | | 12.51 | 6.93 | 9.58 | 1 | 1 | 2 | 2.93 | | | | | [110] |
| Nb | Rh | 0.450 | 0.923 | | | 973 | 1773 | | 0.549 | | | 12.55 | 7.45 | 9.10 | 1 | 1 | 2 | 3.45 | | | | | [125] |
| Nb | Rh | 0.515 | 0.923 | | | | | | | | | 12.64 | 8.57 | 8.07 | 1 | 1 | 2 | 4.57 | | | | | [125] |
| Nb | Si | 0.150 | 0.769 | | | | | | | | | 9.66 | 1.70 | 9.66 | 1 | 0.7 | 0 | 0 | | | | | [128] |
| Nb | Si | 0.160 | 0.769 | | | | | | | | | 9.66 | 1.84 | 9.66 | 1 | 0.84 | 0 | 0 | | | | | [128] |
| Nb | Si | 0.170 | 0.769 | | | | | | | | | 9.66 | 1.98 | 9.66 | 1 | 0.98 | 0 | 0 | | | | | [129] |
| Nb | Si | 0.180 | 0.769 | | | | | | | | | 9.66 | 2.12 | 9.66 | 1 | 1 | 0.12 | 0 | | | | | [128, 129] |
| Nb | Si | 0.190 | 0.769 | | | | | | | | | 9.66 | 2.27 | 9.66 | 1 | 1 | 0.27 | 0 | | | | | [128, 129] |
| Nb | Si | 0.200 | 0.769 | | | 953 | 2273 | | 0.419 | | | 9.66 | 2.42 | 9.66 | 1 | 1 | 0.42 | 0 | | | | | [128, 129] |
| Nb | Si | 0.210 | 0.769 | | | | | | | | | 9.66 | 2.57 | 9.66 | 1 | 1 | 0.57 | 0 | | | | | [129] |
| Nb | Si | 0.220 | 0.769 | | | | | | | | | 9.66 | 2.72 | 9.66 | 1 | 1 | 0.72 | 0 | | | | | [124] |
| Nd | Au | 0.200 | 0.809 | | | | | | | | | 10.12 | 2.53 | 10.12 | 1 | 1 | 0.53 | 0 | | | | | [45] |
| Nd | Fe | 0.490 | 0.702 | | | | | | | | | 9.62 | 6.67 | 6.95 | 1 | 1 | 2 | 2.67 | | | | | [130] |
| Nd | Ni | 0.300 | 0.708 | | | | | | | | | 8.98 | 3.85 | 8.98 | 1 | 1 | 1.85 | 0 | | | | | [115] |
| Nd | Ni | 0.400 | 0.708 | | | | | | | | | 9.32 | 5.33 | 7.99 | 1 | 1 | 2 | 1.33 | | | | | [115] |
| Ni | B | 0.180 | 0.698 | 8.36 | | 533 | 1383 | | 0.385 | | | 8.87 | 1.95 | 8.87 | 1 | 0.95 | 0 | 0 | | | | | [48, 50] |
| Ni | B | 0.185 | 0.698 | | | | | | | | | 8.87 | 2.01 | 8.87 | 1 | 1 | 0.01 | 0 | | | | | [131] |
| Ni | B | 0.190 | 0.698 | | | | | | | | | 8.87 | 2.08 | 8.87 | 1 | 1 | 0.08 | 0 | 0 | 9.3 | 2.18 | 10.8 | [56] |
| Ni | B | 0.200 | 0.698 | | | | | | | | | 8.87 | 2.22 | 8.87 | 1 | 1 | 0.22 | 0 | 0 | 5.8 | 1.45 | 10.8 | [56, 74] |
| Ni | B | 0.280 | 0.698 | | | | | | | | | 8.87 | 3.45 | 8.87 | 1 | 1 | 1.45 | 0 | | | | | [132] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ni | B | 0.300 | 0.698 | | | 585 | 1393 | | 0.420 | | | 8.87 | 3.80 | 8.87 | 1 | 1 | 1.8 | 0 | | | | | 150, 394 |
| Ni | B | 0.330 | 0.698 | | | | | | | | | 8.94 | 4.27 | 8.67 | 1 | 1 | 2 | 0.27 | 0.9 | 9 | 4.43 | 9.4 | [56, 74] |
| Ni | B | 0.340 | 0.698 | | | 658 | 1398 | | 0.471 | | | 8.98 | 4.41 | 8.57 | 1 | 1 | 2 | 0.41 | | | | | [50, 52, 53, 132, 133] |
| Ni | B | 0.360 | 0.698 | | | 662 | 1393 | | 0.475 | | | 9.06 | 4.70 | 8.36 | 1 | 1 | 2 | 0.7 | 1.1 | 8.7 | 4.9 | 9.2 | [53, 56, 133] |
| Ni | B | 0.380 | 0.698 | | | 659 | 1353 | | 0.487 | | | 9.13 | 4.99 | 8.14 | 1 | 1 | 2 | 0.99 | | | | | [50, 53, 132] |
| Ni | B | 0.400 | 0.698 | | | 663 | 1291 | | 0.514 | | | 9.21 | 5.28 | 7.93 | 1 | 1 | 2 | 1.28 | | | | | [50, 53] |
| Ni | B | 0.420 | 0.698 | | | 655 | 1304 | | 0.502 | | | 9.29 | 5.58 | 7.71 | 1 | 1 | 2 | 1.58 | | | | | [50, 53, 132] |
| Ni | Hf | 0.110 | 1.254 | | | 728 | 1523 | | 0.478 | | | 17.09 | 2.11 | 17.09 | 1 | 1 | 0.11 | 0 | | | | | [102] |
| Ni | Hf | 0.300 | 1.254 | | | | | | | | | 16.47 | 6.14 | 14.33 | 1 | 1 | 2 | 2.14 | | | | | [64] |
| Ni | Hf | 0.360 | 1.254 | | | 923 | 1493 | | 0.618 | | | 16.15 | 7.25 | 12.89 | 1 | 1 | 2 | 3.25 | | | | | [102] |
| Ni | Hf | 0.400 | 1.254 | | | | | | | | | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | | | | | [64] |
| Ni | Hf | 0.428 | 1.254 | | | | | | | | | 15.80 | 8.47 | 11.32 | 1 | 1 | 2 | 4.47 | | | | | [64] |
| Ni | Nb | 0.370 | 1.135 | 8.95 | | | | | | | | 14.83 | 6.97 | 11.87 | 1 | 1 | 2 | 2.97 | 6.6 | 5.9 | 10 | 5.6 | [56, 74] |
| Ni | Nb | 0.380 | 1.135 | | 892 | 930 | 1473 | 0.606 | 0.631 | 38 | 0.393 | 14.81 | 7.15 | 11.66 | 1 | 1 | 2 | 3.15 | 6.1 | 5.7 | 9.3 | 5.5 | [56, 134] |
| Ni | Nb | 0.400 | 1.135 | | | 910 | 1484 | | 0.613 | | | 14.76 | 7.50 | 11.25 | 1 | 1 | 2 | 3.5 | | | | | [36, 135] |
| Ni | Nb | 0.400 | 1.135 | | | 933 | 1473 | | 0.633 | | | 14.76 | 7.50 | 11.25 | 1 | 1 | 2 | 3.5 | | | | | [136, 137] |
| Ni | Nb | 0.400 | 1.135 | | | 918 | 1473 | | 0.623 | | | 14.76 | 7.50 | 11.25 | 1 | 1 | 2 | 3.5 | | | | | [127] |
| Ni | Nb | 0.440 | 1.135 | 8.92 | | | | | | | | 14.65 | 8.21 | 10.45 | 1 | 1 | 2 | 4.21 | 5.5 | 6.6 | 8.4 | 6.5 | [56, 74] |
| Ni | P | 0.112 | 0.81 | 8.31 | | | | | | | | 10.12 | 1.28 | 10.12 | 1 | 0.28 | 0 | 0 | | | | | [54] |
| Ni | P | 0.152 | 0.81 | 8.16 | | | | | | | | 10.12 | 1.81 | 10.12 | 1 | 0.81 | 0 | 0 | | | | | [54] |
| Ni | P | 0.180 | 0.81 | | | | | | | | | 10.12 | 2.22 | 10.12 | 1 | 1 | 0.22 | 0 | | | | | [138, 139] |
| Ni | P | 0.185 | 0.81 | 8 | | | | | | | | 10.12 | 2.30 | 10.12 | 1 | 1 | 0.3 | 0 | | | | | [54] |
| Ni | P | 0.190 | 0.81 | | | | | | | | | 10.12 | 2.37 | 10.12 | 1 | 1 | 0.37 | 0 | | | | | [139] |
| Ni | P | 0.200 | 0.81 | 7.9 | | 635 | 1173 | | 0.541 | | | 10.12 | 2.53 | 10.12 | 1 | 1 | 0.53 | 0 | 0 | 9.3 | 2.33 | 9.4 | 340, 114, 306, 393, 3 |
| Ni | P | 0.200 | 0.81 | | | 600 | 1173 | | 0.512 | | | 10.12 | 2.53 | 10.12 | 1 | 1 | 0.53 | 0 | 0 | 9.3 | 2.33 | 9.4 | [36] |
| Ni | P | 0.210 | 0.81 | 7.94 | | | | | | | | 10.12 | 2.69 | 10.12 | 1 | 1 | 0.69 | 0 | | | | | [54] |
| Ni | P | 0.222 | 0.81 | 7.8 | | | | | | | | 10.12 | 2.89 | 10.12 | 1 | 1 | 0.89 | 0 | | | | | [54] |
| Ni | P | 0.240 | 0.81 | 7.8 | | | | | | | | 10.12 | 3.20 | 10.12 | 1 | 1 | 1.2 | 0 | | | | | [54] |
| Ni | P | 0.263 | 0.81 | 7.73 | | | | | | | | 10.12 | 3.61 | 10.12 | 1 | 1 | 1.61 | 0 | | | | | [54] |
| Ni | Ta | 0.100 | 1.151 | | | | | | | | | 15.51 | 1.72 | 15.51 | 1 | 0.72 | 0 | 0 | | | | | [136] |
| Ni | Ta | 0.200 | 1.151 | | | | | | | | | 15.51 | 3.88 | 15.51 | 1 | 1 | 1.88 | 0 | | | | | [136] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ni | Ta | 0.300 | 1.151 | | | 928 | 1778 | | 0.522 | | | 15.22 | 5.77 | 13.45 | 1 | 1 | 2 | 1.77 | | | | | [136] |
| Ni | Ta | 0.350 | 1.151 | | | | | | | | | 15.07 | 6.67 | 12.39 | 1 | 1 | 2 | 2.67 | | | | | [136] |
| Ni | Ta | 0.400 | 1.151 | | | 1023 | 1673 | | 0.611 | | | 14.92 | 7.57 | 11.35 | 1 | 1 | 2 | 3.57 | | | | | [136] |
| Ni | Ti | 0.400 | 1.127 | | | | | | | | | 14.67 | 7.47 | 11.20 | 1 | 1 | 2 | 3.47 | | | | | [140] |
| Ni | Zr | 0.100 | 1.254 | | | 616 | 1518 | | 0.406 | | | 17.09 | 1.90 | 17.09 | 1 | 0.9 | 0 | 0 | | | | | [58] |
| Ni | Zr | 0.100 | 1.254 | | | 736 | 1518 | | 0.485 | | | 17.09 | 1.90 | 17.09 | 1 | 0.9 | 0 | 0 | | | | | [59] |
| Ni | Zr | 0.110 | 1.254 | | | 614 | 1493 | | 0.411 | | | 17.09 | 2.11 | 17.09 | 1 | 1 | 0.11 | 0 | | | | | [58] |
| Ni | Zr | 0.300 | 1.254 | | | | | | | | | 16.47 | 6.14 | 14.33 | 1 | 1 | 2 | 2.14 | | | | | [63] |
| Ni | Zr | 0.320 | 1.254 | | | | | | | | | 16.36 | 6.52 | 13.85 | 1 | 1 | 2 | 2.52 | | | | | [30] |
| Ni | Zr | 0.330 | 1.254 | | | | | | | | | 16.31 | 6.70 | 13.61 | 1 | 1 | 2 | 2.7 | 6.4 | 5.3 | 10.8 | 6.6 | [56] |
| Ni | Zr | 0.340 | 1.254 | | 859 | 876 | 1393 | 0.617 | 0.629 | 17 | 0.389 | 16.25 | 6.89 | 13.37 | 1 | 1 | 2 | 2.89 | | | | | [79] |
| Ni | Zr | 0.350 | 1.254 | | 827 | 863 | 1353 | 0.611 | 0.638 | 36 | 0.396 | 16.20 | 7.07 | 13.13 | 1 | 1 | 2 | 3.07 | | | | | [141] |
| Ni | Zr | 0.350 | 1.254 | | | 850 | 1353 | | 0.628 | | | 16.20 | 7.07 | 13.13 | 1 | 1 | 2 | 3.07 | | | | | [142] |
| Ni | Zr | 0.360 | 1.254 | | 834 | 856 | 1343 | 0.621 | 0.637 | 22 | 0.393 | 16.15 | 7.25 | 12.89 | 1 | 1 | 2 | 3.25 | 6 | 5 | 8.89 | 5 | [56, 79] |
| Ni | Zr | 0.363 | 1.254 | | | | | | | | | 16.13 | 7.31 | 12.82 | 1 | 1 | 2 | 3.31 | 6 | 5 | 8.77 | 5.8 | [56, 74] |
| Ni | Zr | 0.370 | 1.254 | | | 839 | 1363 | | 0.616 | | | 16.10 | 7.44 | 12.66 | 1 | 1 | 2 | 3.44 | | | | | [59, 140] |
| Ni | Zr | 0.390 | 1.254 | | | 808 | 1400 | | 0.577 | | | 15.99 | 7.80 | 12.20 | 1 | 1 | 2 | 3.8 | | | | | [79] |
| Ni | Zr | 0.400 | 1.254 | | | 791 | 1418 | | 0.558 | | | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | | | | | [59, 64] |
| Ni | Zr | 0.400 | 1.254 | | | 835 | 1418 | | 0.589 | | | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | | | | | [142] |
| Ni | Zr | 0.428 | 1.254 | | | | | | | | | 15.80 | 8.47 | 11.32 | 1 | 1 | 2 | 4.47 | | | | | [30, 63] |
| Pb | Au | 0.250 | 0.828 | | | | | | | | | 10.33 | 3.44 | 10.33 | 1 | 1 | 1.44 | 0 | | | | | [35] |
| Pd | As | 0.160 | 0.81 | | | | | | | | | 10.13 | 1.93 | 10.13 | 1 | 0.93 | 0 | 0 | | | | | [143] |
| Pd | As | 0.170 | 0.81 | | | | | | | | | 10.13 | 2.07 | 10.13 | 1 | 1 | 0.07 | 0 | | | | | [143] |
| Pd | As | 0.180 | 0.81 | | | | | | | | | 10.13 | 2.22 | 10.13 | 1 | 1 | 0.22 | 0 | | | | | [143] |
| Pd | As | 0.190 | 0.81 | | | | | | | | | 10.13 | 2.38 | 10.13 | 1 | 1 | 0.38 | 0 | | | | | [143] |
| Pd | As | 0.200 | 0.81 | | | | | | | | | 10.13 | 2.53 | 10.13 | 1 | 1 | 0.53 | 0 | | | | | [143] |
| Pd | Ge | 0.180 | 0.803 | 11.06 | | 603 | | | | | | 10.04 | 2.20 | 10.04 | 1 | 1 | 0.2 | 0 | | | | | [144] |
| Pd | Ge | 0.198 | 0.803 | 11.12 | | 622 | | | | | | 10.04 | 2.48 | 10.04 | 1 | 1 | 0.48 | 0 | | | | | [144] |
| Pd | Ge | 0.200 | 0.803 | | | | | | | | | 10.04 | 2.51 | 10.04 | 1 | 1 | 0.51 | 0 | | | | | [70] |
| Pd | Ge | 0.210 | 0.803 | | | | | | | | | 10.04 | 2.67 | 10.04 | 1 | 1 | 0.67 | 0 | | | | | [145] |
| Pd | Ge | 0.220 | 0.803 | | | | | | | | | 10.04 | 2.83 | 10.04 | 1 | 1 | 0.83 | 0 | | | | | [55] |
| Pd | Ge | 0.221 | 0.803 | 11.07 | | 603 | | | | | | 10.04 | 2.85 | 10.04 | 1 | 1 | 0.85 | 0 | | | | | [144] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pd | Ge | 0.248 | 0.803 | 11.1 | | 523 | | | | | | 10.04 | 3.31 | 10.04 | 1 | 1 | 1.31 | 0 | | | | | [144] |
| Pd | Ge | 0.300 | 0.803 | | | | | | | | | 10.09 | 4.23 | 9.86 | 1 | 1 | 2 | 0.23 | | | | | [70] |
| Pd | Ni | 0.500 | 0.887 | | | | | | | | | 12.27 | 8.14 | 8.14 | 1 | 1 | 2 | 4.14 | | | | | [146] |
| Pd | P | 0.170 | 0.718 | | | | | | | | | 9.09 | 1.86 | 9.09 | 1 | 0.86 | 0 | 0 | | | | | [143] |
| Pd | P | 0.180 | 0.718 | | | | | | | | | 9.09 | 2.00 | 9.09 | 1 | 1 | 0 | 0 | | | | | [143] |
| Pd | P | 0.190 | 0.718 | | | | | | | | | 9.09 | 2.13 | 9.09 | 1 | 1 | 0.13 | 0 | | | | | [147] |
| Pd | Sb | 0.200 | 1.092 | | | | | | | | | 14.64 | 3.66 | 14.64 | 1 | 1 | 1.66 | 0 | | | | | [70] |
| Pd | Sb | 0.300 | 1.092 | | | | | | | | | 14.48 | 5.55 | 12.94 | 1 | 1 | 2 | 1.55 | | | | | [70] |
| Pd | Si | 0.150 | 0.775 | | | 633 | 1213 | | 0.522 | | | 9.72 | 1.72 | 9.72 | 1 | 0.72 | 0 | 0 | | | | | [148, 149] |
| Pd | Si | 0.160 | 0.775 | | 635 | 640 | 1108 | 0.573 | 0.578 | 5 | 0.367 | 9.72 | 1.85 | 9.72 | 1 | 0.85 | 0 | 0 | | | | | [55, 149] |
| Pd | Si | 0.165 | 0.775 | | 635 | 642 | 1105 | 0.575 | 0.581 | 7 | 0.369 | 9.72 | 1.92 | 9.72 | 1 | 0.92 | 0 | 0 | | | | | [150] |
| Pd | Si | 0.170 | 0.775 | | 632 | 645 | 1092 | 0.579 | 0.591 | 13 | 0.374 | 9.72 | 1.99 | 9.72 | 1 | 0.99 | 0 | 0 | | | | | [36, 148] |
| Pd | Si | 0.180 | 0.775 | 10.25 | 648 | 658 | 1113 | 0.582 | 0.591 | 10 | 0.374 | 9.72 | 2.13 | 9.72 | 1 | 1 | 0.13 | 0 | | | | | [149, 151] |
| Pd | Si | 0.180 | 0.775 | | 648 | 658 | 1170 | 0.554 | 0.562 | 10 | 0.362 | 9.72 | 2.13 | 9.72 | 1 | 1 | 0.13 | 0 | | | | | [77, 150] |
| Pd | Si | 0.180 | 0.775 | | 642 | 661 | 1113 | 0.577 | 0.594 | 19 | 0.377 | 9.72 | 2.13 | 9.72 | 1 | 1 | 0.13 | 0 | | | | | [62] |
| Pd | Si | 0.190 | 0.775 | | 650 | | 1153 | 0.564 | | | | 9.72 | 2.28 | 9.72 | 1 | 1 | 0.28 | 0 | | | | | [85] |
| Pd | Si | 0.200 | 0.775 | 10.3 | 655 | 667 | 1220 | 0.537 | 0.547 | 12 | 0.356 | 9.72 | 2.43 | 9.72 | 1 | 1 | 0.43 | 0 | 0 | 6.6 | 1.65 | 10.6 | [56, 70, 72, 77, 148, 149] |
| Pd | Si | 0.200 | 0.775 | | 673 | 673 | 1213 | 0.555 | 0.555 | 0 | 0.357 | 9.72 | 2.43 | 9.72 | 1 | 1 | 0.43 | 0 | | | | | [81, 85] |
| Pd | Si | 0.210 | 0.775 | | | 640 | 1253 | | 0.511 | | | 9.72 | 2.58 | 9.72 | 1 | 1 | 0.58 | 0 | | | | | [145, 149] |
| Pd | Si | 0.230 | 0.775 | | | 673 | 1349 | | 0.499 | | | 9.72 | 2.90 | 9.72 | 1 | 1 | 0.9 | 0 | | | | | [148] |
| Pd | Si | 0.250 | 0.775 | | | | | | | | | 9.72 | 3.24 | 9.72 | 1 | 1 | 1.24 | 0 | | | | | [135] |
| Pd | Si | 0.300 | 0.775 | | | | | | | | | 9.75 | 4.12 | 9.62 | 1 | 1 | 2 | 0.12 | | | | | [70] |
| Pr | Au | 0.200 | 0.787 | | | | | | | | | 9.86 | 2.47 | 9.86 | 1 | 1 | 0.47 | 0 | | | | | [45] |
| Pt | Ge | 0.170 | 0.82 | | | | | | | | | 10.25 | 2.10 | 10.25 | 1 | 1 | 0.1 | 0 | | | | | [12] |
| Pt | Ge | 0.200 | 0.82 | | | | | | | | | 10.25 | 2.56 | 10.25 | 1 | 1 | 0.56 | 0 | 0 | 5.6 | 1.4 | 10.3 | [56, 70] |
| Pt | Ge | 0.300 | 0.82 | | | | | | | | | 10.29 | 4.29 | 10.01 | 1 | 1 | 2 | 0.29 | | | | | [70] |
| Pt | P | 0.200 | 0.734 | | | 483 | 861 | | 0.561 | | | 9.26 | 2.32 | 9.26 | 1 | 1 | 0.32 | 0 | | | | | [36] |
| Pt | P | 0.250 | 0.734 | 15.8 | | | | | | | | 9.26 | 3.09 | 9.26 | 1 | 1 | 1.09 | 0 | | | | | [152] |
| Pt | Sb | 0.200 | 1.115 | | | | | | | | | 14.98 | 3.75 | 14.98 | 1 | 1 | 1.75 | 0 | | | | | [70] |
| Pt | Sb | 0.300 | 1.115 | | | | | | | | | 14.78 | 5.63 | 13.14 | 1 | 1 | 2 | 1.63 | | | | | [70] |
| Pt | Sb | 0.340 | 1.115 | | | 480 | 905 | | 0.530 | | | 14.69 | 6.35 | 12.33 | 1 | 1 | 2 | 2.35 | | | | | [36] |
| Pt | Si | 0.200 | 0.791 | | | | | | | | | 9.91 | 2.48 | 9.91 | 1 | 1 | 0.48 | 0 | | | | | [70] |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pt | Si | 0.230 | 0.791 | | | | | | | | | 9.91 | 2.96 | 9.91 | 1 | 1 | 0.96 | 0 | | | | | [12] |
| Pt | Si | 0.300 | 0.791 | | | | | | | | | 9.95 | 4.18 | 9.76 | 1 | 1 | 2 | 0.18 | | | | | [70] |
| Rh | Si | 0.220 | 0.833 | | | | | | | | | 10.40 | 2.93 | 10.40 | 1 | 1 | 0.93 | 0 | | | | | [12] |
| Sc | Fe | 0.250 | 0.772 | | | | | | | | | 9.69 | 3.23 | 9.69 | 1 | 1 | 1.23 | 0 | | | | | [89] |
| Sm | Au | 0.200 | 0.778 | | | | | | | | | 9.77 | 2.44 | 9.77 | 1 | 1 | 0.44 | 0 | | | | | [45] |
| Sn | Fe | 0.450 | 0.806 | | | 390 | 1753 | | 0.222 | | | 10.55 | 6.55 | 8.00 | 1 | 1 | 2 | 2.55 | | | | | [153] |
| Sn | Fe | 0.500 | 0.806 | | | 435 | 1778 | | 0.245 | | | 10.70 | 7.35 | 7.35 | 1 | 1 | 2 | 3.35 | | | | | [153] |
| Sr | Al | 0.180 | 0.665 | | 455 | | 863 | 0.527 | | | | 8.51 | 1.87 | 8.51 | 1 | 0.87 | 0 | 0 | | | | | [39] |
| Sr | Al | 0.300 | 0.665 | | 530 | | 953 | 0.556 | | | | 8.51 | 3.65 | 8.51 | 1 | 1 | 1.65 | 0 | | | | | [39] |
| Sr | Al | 0.350 | 0.665 | | 490 | | 993 | 0.493 | | | | 8.63 | 4.42 | 8.21 | 1 | 1 | 2 | 0.42 | | | | | [40] |
| Sr | Ga | 0.180 | 0.632 | | 445 | | 793 | 0.561 | | | | 8.16 | 1.79 | 8.16 | 1 | 0.79 | 0 | 0 | | | | | [39] |
| Sr | Mg | 0.300 | 0.755 | | 390 | | 699 | 0.558 | | | | 9.51 | 4.05 | 9.46 | 1 | 1 | 2 | 0.05 | | | | | [39] |
| Sr | Mg | 0.350 | 0.755 | | 383 | | 756 | 0.507 | | | | 9.67 | 4.78 | 8.89 | 1 | 1 | 2 | 0.78 | | | | | [40] |
| Sr | Zn | 0.250 | 0.651 | | 380 | | 738 | 0.515 | | | | 8.36 | 2.79 | 8.36 | 1 | 1 | 0.79 | 0 | | | | | [39] |
| Ta | Ir | 0.450 | 0.938 | | | 1283 | 2228 | | 0.576 | | | 12.70 | 7.52 | 9.19 | 1 | 1 | 2 | 3.52 | | | | | [125] |
| Ta | Ir | 0.500 | 0.938 | | | | | | | | | 12.76 | 8.38 | 8.38 | 1 | 1 | 2 | 4.38 | | | | | [154] |
| Ta | Ni | 0.400 | 0.869 | | | | | | | | | 11.08 | 6.03 | 9.05 | 1 | 1 | 2 | 2.03 | | | | | [126] |
| Ta | Ni | 0.500 | 0.869 | | | 985 | 1923 | | 0.512 | | | 12.09 | 8.04 | 8.04 | 1 | 1 | 2 | 4.04 | 4.9 | 6 | 6 | 8.2 | [126, 155] |
| Ta | Rh | 0.450 | 0.91 | | | 1118 | 2013 | | 0.555 | | | 12.42 | 7.39 | 9.03 | 1 | 1 | 2 | 3.39 | | | | | [125] |
| Tb | Au | 0.200 | 0.8 | | | | | | | | | 10.01 | 2.50 | 10.01 | 1 | 1 | 0.5 | 0 | | | | | [45] |
| Tb | Au | 0.250 | 0.8 | | | | | | | | | 10.01 | 3.34 | 10.01 | 1 | 1 | 1.34 | 0 | | | | | [99] |
| Tb | Cu | 0.350 | 0.7 | | | | | | | | | 9.04 | 4.56 | 8.47 | 1 | 1 | 2 | 0.56 | | | | | [156] |
| Te | Cu | 0.320 | 0.9 | | | | | | | | | 12.09 | 5.15 | 10.94 | 1 | 1 | 2 | 1.15 | | | | | [67] |
| Te | Ge | 0.150 | 0.814 | | | | | | | | | 10.18 | 1.80 | 10.18 | 1 | 0.8 | 0 | 0 | | | | | [157] |
| Te | Tl | 0.150 | 1.229 | | | | | | | | | 16.70 | 2.95 | 16.70 | 1 | 1 | 0.95 | 0 | | | | | [158] |
| Te | Tl | 0.200 | 1.229 | | | | | | | | | 16.66 | 4.13 | 16.53 | 1 | 1 | 2 | 0.13 | | | | | [158] |
| Te | Tl | 0.250 | 1.229 | | | | | | | | | 16.41 | 5.10 | 15.31 | 1 | 1 | 2 | 1.1 | | | | | [158] |
| Te | Tl | 0.270 | 1.229 | | | | | | | | | 16.31 | 5.48 | 14.83 | 1 | 1 | 2 | 1.48 | | | | | [158] |
| Te | Tl | 0.290 | 1.229 | | | | | | | | | 16.21 | 5.86 | 14.35 | 1 | 1 | 2 | 1.86 | | | | | [158] |
| Te | Tl | 0.300 | 1.229 | | | | | | | | | 16.16 | 6.05 | 14.11 | 1 | 1 | 2 | 2.05 | | | | | [158] |
| Te | Tl | 0.330 | 1.229 | | | | | | | | | 16.02 | 6.61 | 13.41 | 1 | 1 | 2 | 2.61 | | | | | [158] |
| Te | Tl | 0.360 | 1.229 | | | | | | | | | 15.88 | 7.16 | 12.72 | 1 | 1 | 2 | 3.16 | | | | | [158] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Te | Tl | 0.380 | 1.229 | | | | | | | | | 15.79 | 7.52 | 12.27 | 1 | 1 | 2 | 3.52 | | | | | [158] |
| Te | Tl | 0.400 | 1.229 | | | | | | | | | 15.69 | 7.88 | 11.82 | 1 | 1 | 2 | 3.88 | | | | | [158] |
| Th | Fe | 0.200 | 0.702 | | | 647 | 1553 | | 0.417 | | | 8.92 | 2.23 | 8.92 | 1 | 1 | 0.23 | 0 | | | | | [90, 91] |
| Th | Fe | 0.250 | 0.702 | | | 645 | 1418 | | 0.455 | | | 8.92 | 2.97 | 8.92 | 1 | 1 | 0.97 | 0 | | | | | [91] |
| Th | Fe | 0.300 | 0.702 | | | 638 | 1213 | | 0.526 | | | 8.92 | 3.82 | 8.92 | 1 | 1 | 1.82 | 0 | | | | | [90, 91] |
| Th | Fe | 0.330 | 0.702 | | | 631 | 1205 | | 0.524 | | | 8.99 | 4.29 | 8.70 | 1 | 1 | 2 | 0.29 | | | | | [91] |
| Th | Fe | 0.350 | 0.702 | | | 643 | 1198 | | 0.537 | | | 9.06 | 4.57 | 8.49 | 1 | 1 | 2 | 0.57 | | | | | [91] |
| Th | Fe | 0.400 | 0.702 | | | 654 | 1173 | | 0.558 | | | 9.25 | 5.30 | 7.95 | 1 | 1 | 2 | 1.3 | | | | | [90, 91] |
| Th | Fe | 0.450 | 0.702 | | | 691 | 1233 | | 0.560 | | | 9.45 | 6.05 | 7.40 | 1 | 1 | 2 | 2.05 | | | | | [90, 91] |
| Th | Fe | 0.480 | 0.702 | | | 698 | 1173 | | 0.595 | | | 9.58 | 6.52 | 7.06 | 1 | 1 | 2 | 2.52 | | | | | [90, 91] |
| Th | Fe | 0.500 | 0.702 | | | | | | | | | 9.66 | 6.83 | 6.83 | 1 | 1 | 2 | 2.83 | | | | | [90] |
| Th | Fe | 0.550 | 0.702 | | | 745 | 1383 | | 0.539 | | | 9.88 | 7.64 | 6.25 | 1 | 1 | 2 | 3.64 | | | | | [90] |
| Th | Fe | 0.600 | 0.702 | | | 745 | 1383 | | 0.539 | | | 10.11 | 8.47 | 5.64 | 1 | 1 | 2 | 4.47 | | | | | [90, 91] |
| Ti | Be | 0.370 | 0.789 | 3.83 | | 668 | 1353 | | 0.493 | | | 10.12 | 5.22 | 8.90 | 1 | 1 | 2 | 1.22 | | | | | [63, 135, 159] |
| Ti | Be | 0.380 | 0.789 | | | | | | | | | 10.15 | 5.38 | 8.77 | 1 | 1 | 2 | 1.38 | | | | | [159] |
| Ti | Be | 0.390 | 0.789 | | | | | | | | | 10.18 | 5.53 | 8.65 | 1 | 1 | 2 | 1.53 | | | | | [159] |
| Ti | Be | 0.400 | 0.789 | 3.77 | | 669 | | | | | | 10.21 | 5.68 | 8.53 | 1 | 1 | 2 | 1.68 | | | | | [63, 159, 160] |
| Ti | Be | 0.410 | 0.789 | 3.72 | | 670 | | | | | | 10.24 | 5.84 | 8.40 | 1 | 1 | 2 | 1.84 | | | | | [63, 160] |
| Ti | Be | 0.420 | 0.789 | | | | | | | | | 10.27 | 5.99 | 8.28 | 1 | 1 | 2 | 1.99 | | | | | [160] |
| Ti | Be | 0.430 | 0.789 | | | | | | | | | 10.30 | 6.15 | 8.15 | 1 | 1 | 2 | 2.15 | | | | | [160] |
| Ti | Cu | 0.300 | 0.887 | | | | | | | | | 11.10 | 4.53 | 10.57 | 1 | 1 | 2 | 0.53 | | | | | [69] |
| Ti | Cu | 0.350 | 0.887 | | | 639 | 1281 | | 0.499 | | | 11.18 | 5.31 | 9.87 | 1 | 1 | 2 | 1.31 | | | | | [68, 71] |
| Ti | Cu | 0.390 | 0.887 | | | 657 | 1257 | | 0.523 | | | 12.06 | 6.26 | 9.80 | 1 | 1 | 2 | 2.26 | | | | | [71] |
| Ti | Cu | 0.400 | 0.887 | | | | | | | | | 12.08 | 6.43 | 9.65 | 1 | 1 | 2 | 2.43 | | | | | [68, 69] |
| Ti | Cu | 0.430 | 0.887 | | | 680 | 1233 | | 0.552 | | | 12.13 | 6.94 | 9.20 | 1 | 1 | 2 | 2.94 | | | | | [71] |
| Ti | Cu | 0.450 | 0.887 | | | | | | | | | 12.17 | 7.28 | 8.90 | 1 | 1 | 2 | 3.28 | | | | | [68] |
| Ti | Cu | 0.500 | 0.887 | 6.25 | | 680 | 1257 | | 0.541 | | | 12.27 | 8.14 | 8.14 | 1 | 1 | 2 | 4.14 | 4.5 | 6 | 6 | 6.4 | [56, 68, 69, 71, 72, 161] |
| Ti | Ni | 0.250 | 0.887 | | | | | | | | | 11.04 | 3.68 | 11.04 | 1 | 1 | 1.68 | 0 | | | | | [161] |
| Ti | Ni | 0.260 | 0.887 | | | | | | | | | 11.04 | 3.88 | 11.04 | 1 | 1 | 1.88 | 0 | | | | | [162] |
| Ti | Ni | 0.300 | 0.887 | | | 720 | 1247 | | 0.577 | | | 11.10 | 4.53 | 10.57 | 1 | 1 | 2 | 0.53 | | | | | [63, 68, 161, 163] |
| Ti | Ni | 0.330 | 0.887 | | | 723 | 1256 | | 0.576 | | | 11.15 | 5.00 | 10.15 | 1 | 1 | 2 | 1 | | | | | [68, 140, 162, 163] |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ti | Ni | 0.350 | 0.887 | | | 760 | 1328 | | 0.572 | | | 11.18 | 5.31 | 9.87 | 1 | 1 | 2 | 1.31 | | | | | [69, 161] |
| Ti | Ni | 0.400 | 0.887 | | | 762 | 1472 | | 0.518 | | | 12.08 | 6.43 | 9.65 | 1 | 1 | 2 | 2.43 | 2.3 | 7.9 | 5.27 | 8.1 | [56, 68, 161, 163] |
| Ti | Ni | 0.450 | 0.887 | | | | | | | | | 12.17 | 7.28 | 8.90 | 1 | 1 | 2 | 3.28 | | | | | [63, 68] |
| Ti | Pt | 0.330 | 0.979 | | | | | | | | | 13.08 | 5.63 | 11.44 | 1 | 1 | 2 | 1.63 | | | | | [69] |
| Ti | Si | 0.130 | 0.775 | | | 702 | 1620 | | 0.433 | | | 9.72 | 1.45 | 9.72 | 1 | 0.45 | 0 | 0 | | | | | [164, 165] |
| Ti | Si | 0.150 | 0.775 | | | 702 | 1677 | | 0.419 | | | 9.72 | 1.72 | 9.72 | 1 | 0.72 | 0 | 0 | | | | | [105, 165] |
| Ti | Si | 0.160 | 0.775 | | | | | | | | | 9.72 | 1.85 | 9.72 | 1 | 0.85 | 0 | 0 | 0 | 9.4 | 1.79 | 11.5 | [56, 74] |
| Ti | Si | 0.200 | 0.775 | | | 867 | 1903 | | 0.456 | | | 9.72 | 2.43 | 9.72 | 1 | 1 | 0.43 | 0 | | | | | [63, 69, 105, 159, 161] |
| Ti | Si | 0.220 | 0.775 | | | | | | | | | 9.72 | 2.74 | 9.72 | 1 | 1 | 0.74 | 0 | | | | | [164] |
| Tm | Au | 0.200 | 0.823 | | | | | | | | | 10.28 | 2.57 | 10.28 | 1 | 1 | 0.57 | 0 | | | | | [45] |
| U | Co | 0.200 | 0.791 | | | | | | | | | 9.91 | 2.48 | 9.91 | 1 | 1 | 0.48 | 0 | | | | | [166] |
| U | Cr | 0.270 | 0.823 | | | | | | | | | 10.28 | 3.80 | 10.28 | 1 | 1 | 1.8 | 0 | | | | | [166] |
| U | Fe | 0.200 | 0.791 | | | | | | | | | 9.91 | 2.48 | 9.91 | 1 | 1 | 0.48 | 0 | | | | | [166] |
| U | Mn | 0.200 | 0.835 | | | | | | | | | 10.42 | 2.61 | 10.42 | 1 | 1 | 0.61 | 0 | | | | | [166] |
| U | Ni | 0.200 | 0.797 | | | | | | | | | 9.98 | 2.50 | 9.98 | 1 | 1 | 0.5 | 0 | | | | | [166] |
| Y | Cu | 0.330 | 0.704 | | | 535 | | | | | | 9.01 | 4.29 | 8.72 | 1 | 1 | 2 | 0.29 | 2.9 | 8.4 | 4.14 | 10.7 | [56, 75] |
| Y | Cu | 0.400 | 0.704 | 6.06 | | 517 | | | | | | 9.27 | 5.31 | 7.96 | 1 | 1 | 2 | 1.31 | | | | | [113, 167] |
| Y | Cu | 0.570 | 0.704 | | | 522 | | | | | | 9.99 | 7.97 | 6.01 | 1 | 1 | 2 | 3.97 | 2.9 | 8.4 | 11.1 | 10.7 | [75] |
| Y | Ni | 0.330 | 0.704 | | | | | | | | | 9.01 | 4.29 | 8.72 | 1 | 1 | 2 | 0.29 | 1.9 | 9.3 | 4.58 | 9.5 | [56, 74] |
| Zn | Ca | 0.375 | 1.457 | | | | | | | | | 18.05 | 8.27 | 13.78 | 1 | 1 | 2 | 4.27 | | | | | [40] |
| Zn | Ca | 0.390 | 1.457 | | | | | | | | | 17.91 | 8.54 | 13.36 | 1 | 1 | 2 | 4.54 | | | | | [40] |
| Zr | Al | 0.260 | 0.892 | | | | | | | | | 11.10 | 3.90 | 11.10 | 1 | 1 | 1.9 | 0 | | | | | [12] |
| Zr | Au | 0.300 | 0.911 | | | | | | | | | 12.20 | 4.86 | 11.34 | 1 | 1 | 2 | 0.86 | | | | | [168] |
| Zr | Be | 0.300 | 0.709 | 5.72 | 613 | 648 | 1393 | 0.440 | 0.465 | 35 | 0.323 | 8.99 | 3.85 | 8.99 | 1 | 1 | 1.85 | 0 | | | | | [63, 160] |
| Zr | Be | 0.300 | 0.709 | 5.72 | 600 | | 1393 | 0.431 | | | | 8.99 | 3.85 | 8.99 | 1 | 1 | 1.85 | 0 | | | | | [169] |
| Zr | Be | 0.325 | 0.709 | | | | | | | | | 9.05 | 4.24 | 8.81 | 1 | 1 | 2 | 0.24 | | | | | [170] |
| Zr | Be | 0.350 | 0.709 | 5.65 | 614 | | 1238 | 0.496 | | | | 9.14 | 4.60 | 8.54 | 1 | 1 | 2 | 0.6 | | | | | [169] |
| Zr | Be | 0.350 | 0.709 | 5.48 | 618 | 647 | 1238 | 0.499 | 0.523 | 29 | 0.349 | 9.14 | 4.60 | 8.54 | 1 | 1 | 2 | 0.6 | | | | | [63, 135, 160] |
| Zr | Be | 0.400 | 0.709 | 5.46 | 623 | 673 | 1343 | 0.464 | 0.501 | 50 | 0.342 | 9.33 | 5.33 | 8.00 | 1 | 1 | 2 | 1.33 | | | | | [63, 160] |
| Zr | Be | 0.400 | 0.709 | 5.48 | 625 | | 1393 | 0.449 | | | | 9.33 | 5.33 | 8.00 | 1 | 1 | 2 | 1.33 | | | | | [169] |
| Zr | Be | 0.430 | 0.709 | | | | | | | | | 9.45 | 5.78 | 7.66 | 1 | 1 | 2 | 1.78 | 2 | 7.1 | 5.35 | 6.2 | [38] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zr | Be | 0.450 | 0.709 | 5.18 | 646 | 681 | 1413 | 0.457 | 0.482 | 35 | 0.331 | 9.52 | 6.09 | 7.44 | 1 | 1 | 2 | 2.09 | | | | | [63, 160] |
| Zr | Be | 0.500 | 0.709 | 5.08 | 672 | 682 | 1473 | 0.456 | 0.463 | 10 | 0.318 | 9.73 | 6.87 | 6.87 | 1 | 1 | 2 | 2.87 | | | | | [63, 160] |
| Zr | Co | 0.200 | 0.791 | 6.8 | | 580 | 1388 | | 0.418 | | | 9.91 | 2.48 | 9.91 | 1 | 1 | 0.48 | 0 | | | | | [171-173] |
| Zr | Co | 0.220 | 0.791 | | | 643 | 1254 | | 0.513 | | | 9.91 | 2.80 | 9.91 | 1 | 1 | 0.8 | 0 | | | | | [59, 79] |
| Zr | Co | 0.270 | 0.791 | | | | | | | | | 9.91 | 3.67 | 9.91 | 1 | 1 | 1.67 | 0 | | | | | [63] |
| Zr | Co | 0.300 | 0.791 | 7 | | | | | | | | 9.95 | 4.18 | 9.76 | 1 | 1 | 2 | 0.18 | | | | | [172] |
| Zr | Co | 0.300 | 0.791 | 6.68 | | 700 | 1394 | | 0.502 | | | 9.95 | 4.18 | 9.76 | 1 | 1 | 2 | 0.18 | | | | | [59, 154, 172] |
| Zr | Co | 0.330 | 0.791 | 7.12 | | | | | | | | 10.03 | 4.63 | 9.40 | 1 | 1 | 2 | 0.63 | | | | | [171, 172] |
| Zr | Co | 0.350 | 0.791 | 7.2 | | | | | | | | 10.09 | 4.93 | 9.16 | 1 | 1 | 2 | 0.93 | | | | | [172] |
| Zr | Co | 0.360 | 0.791 | | | 740 | 1394 | | 0.531 | | | 10.12 | 5.08 | 9.04 | 1 | 1 | 2 | 1.08 | | | | | [59] |
| Zr | Co | 0.400 | 0.791 | 7.35 | | 767 | 1523 | | 0.504 | | | 10.24 | 5.70 | 8.54 | 1 | 1 | 2 | 1.7 | | | | | [79, 171, 172] |
| Zr | Co | 0.450 | 0.791 | 7.4 | | | | | | | | 10.39 | 6.48 | 7.91 | 1 | 1 | 2 | 2.48 | | | | | [172] |
| Zr | Co | 0.470 | 0.791 | 7.63 | | | | | | | | 10.45 | 6.79 | 7.66 | 1 | 1 | 2 | 2.79 | | | | | [172] |
| Zr | Co | 0.500 | 0.791 | | | | | | | | | 10.55 | 7.27 | 7.27 | 1 | 1 | 2 | 3.27 | | | | | [140] |
| Zr | Co | 0.520 | 0.791 | 7.7 | | | | | | | | 10.61 | 7.60 | 7.01 | 1 | 1 | 2 | 3.6 | | | | | [172] |
| Zr | Co | 0.530 | 0.791 | | | 785 | 1585 | | 0.495 | | | 10.64 | 7.76 | 6.88 | 1 | 1 | 2 | 3.76 | | | | | [59] |
| Zr | Co | 0.573 | 0.791 | | | | | | | | | 10.79 | 8.47 | 6.31 | 1 | 1 | 2 | 4.47 | | | | | [63] |
| Zr | Cu | 0.200 | 0.797 | | | | | | | | | 9.98 | 2.50 | 9.98 | 1 | 1 | 0.5 | 0 | | | | | [76] |
| Zr | Cu | 0.250 | 0.797 | | 571 | 618 | 1363 | 0.419 | 0.454 | 47 | 0.320 | 9.98 | 3.33 | 9.98 | 1 | 1 | 1.33 | 0 | | | | | [75] |
| Zr | Cu | 0.280 | 0.797 | | 600 | 666 | 1268 | 0.473 | 0.525 | 66 | 0.356 | 9.98 | 3.88 | 9.98 | 1 | 1 | 1.88 | 0 | | | | | [75] |
| Zr | Cu | 0.300 | 0.797 | | | | | | | | | 10.02 | 4.21 | 9.82 | 1 | 1 | 2 | 0.21 | | | | | [64] |
| Zr | Cu | 0.335 | 0.797 | | 631 | 690 | 1273 | 0.496 | 0.542 | 59 | 0.362 | 10.12 | 4.73 | 9.39 | 1 | 1 | 2 | 0.73 | | | | | [76] |
| Zr | Cu | 0.400 | 0.797 | | 677 | | 1248 | 0.542 | | | | 10.31 | 5.72 | 8.58 | 1 | 1 | 2 | 1.72 | | | | | [64, 70, 81] |
| Zr | Cu | 0.400 | 0.797 | | 646 | 707 | 1248 | 0.518 | 0.567 | 61 | 0.373 | 10.31 | 5.72 | 8.58 | 1 | 1 | 2 | 1.72 | | | | | [76] |
| Zr | Cu | 0.400 | 0.797 | | 654 | 718 | 1343 | 0.487 | 0.534 | 64 | 0.359 | 10.31 | 5.72 | 8.58 | 1 | 1 | 2 | 1.72 | | | | | [75] |
| Zr | Cu | 0.450 | 0.797 | | 661 | 729 | 1203 | 0.549 | 0.606 | 68 | 0.391 | 10.46 | 6.51 | 7.95 | 1 | 1 | 2 | 2.51 | | | | | [75] |
| Zr | Cu | 0.450 | 0.797 | | 669 | 719 | 1206 | 0.555 | 0.596 | 50 | 0.383 | 10.46 | 6.51 | 7.95 | 1 | 1 | 2 | 2.51 | | | | | [66] |
| Zr | Cu | 0.460 | 0.797 | | 696 | 746 | 1201 | 0.580 | 0.621 | 50 | 0.393 | 10.49 | 6.66 | 7.82 | 1 | 1 | 2 | 2.66 | | | | | [135] |
| Zr | Cu | 0.480 | 0.797 | | 689 | 749 | 1207 | 0.571 | 0.620 | 59 | 0.395 | 10.55 | 6.98 | 7.56 | 1 | 1 | 2 | 2.98 | | | | | [75] |
| Zr | Cu | 0.500 | 0.797 | | 707 | 749 | 1208 | 0.585 | 0.620 | 42 | 0.391 | 10.61 | 7.30 | 7.30 | 1 | 1 | 2 | 3.3 | | | | | [64, 79] |
| Zr | Cu | 0.500 | 0.797 | 7.33 | 681 | 735 | 1214 | 0.561 | 0.605 | 54 | 0.388 | 10.61 | 7.30 | 7.30 | 1 | 1 | 2 | 3.3 | | | | | [72, 77, 127] |
| Zr | Cu | 0.500 | 0.797 | | 680 | 730 | 1214 | 0.560 | 0.602 | 50 | 0.386 | 10.61 | 7.30 | 7.30 | 1 | 1 | 2 | 3.3 | | | | | [76] |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zr | Cu | 0.500 | 0.797 | | 711 | 774 | 1214 | 0.586 | 0.638 | 63 | 0.402 | 10.61 | 7.30 | 7.30 | 1 | 1 | 2 | 3.3 | | | | | [75] |
| Zr | Cu | 0.550 | 0.797 | | 698 | 748 | 1183 | 0.590 | 0.632 | 50 | 0.398 | 10.77 | 8.12 | 6.65 | 1 | 1 | 2 | 4.12 | | | | | [76] |
| Zr | Cu | 0.560 | 0.797 | | 727 | | 1163 | 0.625 | | | | 10.80 | 8.29 | 6.51 | 1 | 1 | 2 | 4.29 | | | | | [81] |
| Zr | Cu | 0.560 | 0.797 | | 728 | 792 | 1163 | 0.626 | 0.681 | 64 | 0.419 | 10.80 | 8.29 | 6.51 | 1 | 1 | 2 | 4.29 | | | | | [75] |
| Zr | Cu | 0.570 | 0.797 | | | | | | | | | 10.83 | 8.45 | 6.38 | 1 | 1 | 2 | 4.45 | 5.4 | 5 | 6.7 | 5.9 | [70, 73, 174] |
| Zr | Fe | 0.200 | 0.791 | | | | | | | | | 9.91 | 2.48 | 9.91 | 1 | 1 | 0.48 | 0 | | | | | [171] |
| Zr | Fe | 0.240 | 0.791 | | | | | | | | | 9.91 | 3.13 | 9.91 | 1 | 1 | 1.13 | 0 | | | | | [94, 95, 175] |
| Zr | Fe | 0.250 | 0.791 | | | | | | | | | 9.91 | 3.30 | 9.91 | 1 | 1 | 1.3 | 0 | | | | | [63, 89, 171] |
| Zr | Fe | 0.280 | 0.791 | | | | | | | | | 9.91 | 3.85 | 9.91 | 1 | 1 | 1.85 | 0 | | | | | [94] |
| Zr | Fe | 0.300 | 0.791 | 6.45 | | 663 | 1433 | | 0.463 | | | 9.95 | 4.18 | 9.76 | 1 | 1 | 2 | 0.18 | | | | | [154, 175] |
| Zr | Fe | 0.330 | 0.791 | | | 682 | 1553 | | 0.439 | | | 10.03 | 4.63 | 9.40 | 1 | 1 | 2 | 0.63 | | | | | [79] |
| Zr | Fe | 0.350 | 0.791 | | | | | | | | | 10.09 | 4.93 | 9.16 | 1 | 1 | 2 | 0.93 | | | | | [63, 95] |
| Zr | Fe | 0.400 | 0.791 | | | | | | | | | 10.24 | 5.70 | 8.54 | 1 | 1 | 2 | 1.7 | | | | | [95] |
| Zr | Ge | 0.130 | 0.722 | | | | | | | | | 9.13 | 1.36 | 9.13 | 1 | 0.36 | 0 | 0 | | | | | [105, 176] |
| Zr | Ge | 0.150 | 0.722 | | | | | | | | | 9.13 | 1.61 | 9.13 | 1 | 0.61 | 0 | 0 | | | | | [105, 176] |
| Zr | Ge | 0.170 | 0.722 | | | | | | | | | 9.13 | 1.87 | 9.13 | 1 | 0.87 | 0 | 0 | | | | | [105, 176] |
| Zr | Mn | 0.450 | 0.835 | | | | | | | | | 10.84 | 6.68 | 8.16 | 1 | 1 | 2 | 2.68 | | | | | [63] |
| Zr | Mn | 0.500 | 0.835 | | | | | | | | | 10.97 | 7.49 | 7.49 | 1 | 1 | 2 | 3.49 | | | | | [63] |
| Zr | Mo | 0.400 | 0.88 | | | | | | | | | 11.19 | 6.08 | 9.11 | 1 | 1 | 2 | 2.08 | | | | | [63] |
| Zr | Mo | 0.533 | 0.88 | | | | | | | | | 12.26 | 8.67 | 7.60 | 1 | 1 | 2 | 4.67 | | | | | [63] |
| Zr | Ni | 0.180 | 0.797 | | | | | | | | | 9.98 | 2.19 | 9.98 | 1 | 1 | 0.19 | 0 | | | | | [30] |
| Zr | Ni | 0.200 | 0.797 | | | 660 | 1423 | | 0.464 | | | 9.98 | 2.50 | 9.98 | 1 | 1 | 0.5 | 0 | | | | | [70, 142, 171] |
| Zr | Ni | 0.220 | 0.797 | | | 611 | 1343 | | 0.455 | | | 9.98 | 2.82 | 9.98 | 1 | 1 | 0.82 | 0 | | | | | [59] |
| Zr | Ni | 0.240 | 0.797 | | | 638 | 1233 | | 0.517 | | | 9.98 | 3.15 | 9.98 | 1 | 1 | 1.15 | 0 | | | | | [59, 63] |
| Zr | Ni | 0.250 | 0.797 | | | | | | | | | 9.98 | 3.33 | 9.98 | 1 | 1 | 1.33 | 0 | | | | | [171] |
| Zr | Ni | 0.280 | 0.797 | | 642 | 664 | 1313 | 0.489 | 0.506 | 22 | 0.340 | 9.98 | 3.88 | 9.98 | 1 | 1 | 1.88 | 0 | | | | | [79] |
| Zr | Ni | 0.300 | 0.797 | 6.71 | | 660 | 1338 | | 0.493 | | | 10.02 | 4.21 | 9.82 | 1 | 1 | 2 | 0.21 | | | | | [64, 142, 154] |
| Zr | Ni | 0.330 | 0.797 | | | | | | | | | 10.11 | 4.65 | 9.45 | 1 | 1 | 2 | 0.65 | | | | | [140, 171] |
| Zr | Ni | 0.333 | 0.797 | | | | | | | | | 10.11 | 4.70 | 9.41 | 1 | 1 | 2 | 0.7 | 1.3 | 8.4 | 4.2 | 11.6 | [74, 177] |
| Zr | Ni | 0.350 | 0.797 | | | | | | | | | 10.16 | 4.96 | 9.21 | 1 | 1 | 2 | 0.96 | 3.3 | 8.6 | 4.8 | 11 | [177] |
| Zr | Ni | 0.360 | 0.797 | | | 730 | 1293 | | 0.565 | | | 10.19 | 5.11 | 9.08 | 1 | 1 | 2 | 1.11 | 2.3 | 7.9 | 3.9 | 9.1 | [59, 177] |
| Zr | Ni | 0.370 | 0.797 | | 700 | 720 | 1313 | 0.533 | 0.548 | 20 | 0.358 | 10.22 | 5.26 | 8.96 | 1 | 1 | 2 | 1.26 | | | | | [79] |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zr | Ni | 0.400 | 0.797 | | 713 | 735 | 1413 | 0.505 | 0.520 | 22 | 0.346 | 10.31 | 5.72 | 8.58 | 1 | 1 | 2 | 1.72 | | | | | [64, 70, 79, 142] |
| Zr | Ni | 0.500 | 0.797 | | | 795 | 1523 | | 0.522 | | | 10.61 | 7.30 | 7.30 | 1 | 1 | 2 | 3.3 | 3.3 | 6.7 | 6.7 | 7.8 | [56, 64, 140, 142] |
| Zr | Ni | 0.571 | 0.797 | | | | | | | | | 10.83 | 8.47 | 6.36 | 1 | 1 | 2 | 4.47 | | | | | [30, 63] |
| Zr | Pd | 0.200 | 0.899 | | | | | | | | | 11.18 | 2.79 | 11.18 | 1 | 1 | 0.79 | 0 | | | | | [70] |
| Zr | Pd | 0.250 | 0.899 | | | | | | | | | 11.18 | 3.73 | 11.18 | 1 | 1 | 1.73 | 0 | | | | | [63] |
| Zr | Pd | 0.300 | 0.899 | 7.53 | | | | | | | | 12.04 | 4.81 | 11.23 | 1 | 1 | 2 | 0.81 | | | | | [110, 154, 168] |
| Zr | Pd | 0.300 | 0.899 | 7.71 | 680 | 690 | | | | 10 | | 12.04 | 4.81 | 11.23 | 1 | 1 | 2 | 0.81 | 3.6 | 5.37 | 2.3 | 11.5 | [36, 178] |
| Zr | Pd | 0.330 | 0.899 | 7.9 | | | | | | | | 12.09 | 5.31 | 10.78 | 1 | 1 | 2 | 1.31 | | | | | [140, 179] |
| Zr | Pd | 0.350 | 0.899 | 8.02 | | | | | | | | 12.12 | 5.64 | 10.48 | 1 | 1 | 2 | 1.64 | | | | | [70, 179] |
| Zr | Pd | 0.450 | 0.899 | | | | | | | | | 12.29 | 7.33 | 8.96 | 1 | 1 | 2 | 3.33 | | | | | [63] |
| Zr | Pt | 0.200 | 0.88 | | | | | | | | | 10.95 | 2.74 | 10.95 | 1 | 1 | 0.74 | 0 | | | | | [168, 178] |
| Zr | Rh | 0.170 | 0.835 | | | | | | | | | 10.42 | 2.14 | 10.42 | 1 | 1 | 0.14 | 0 | | | | | [63] |
| Zr | Rh | 0.180 | 0.835 | | | | | | | | | 10.42 | 2.29 | 10.42 | 1 | 1 | 0.29 | 0 | | | | | [180] |
| Zr | Rh | 0.270 | 0.835 | | | | | | | | | 10.42 | 3.86 | 10.42 | 1 | 1 | 1.86 | 0 | | | | | [180] |
| Zr | Rh | 0.280 | 0.835 | | | | | | | | | 10.43 | 4.04 | 10.39 | 1 | 1 | 2 | 0.04 | | | | | [63] |
| Zr | Si | 0.120 | 0.696 | | | 804 | 1936 | | 0.416 | | | 8.85 | 1.21 | 8.85 | 1 | 0.21 | 0 | 0 | | | | | [181] |
| Zr | Si | 0.130 | 0.696 | | | 772 | 1984 | | 0.389 | | | 8.85 | 1.32 | 8.85 | 1 | 0.32 | 0 | 0 | | | | | [105, 181] |
| Zr | Si | 0.140 | 0.696 | | | 757 | 2019 | | 0.375 | | | 8.85 | 1.44 | 8.85 | 1 | 0.44 | 0 | 0 | | | | | [181] |
| Zr | Si | 0.150 | 0.696 | | | 759 | 2047 | | 0.371 | | | 8.85 | 1.56 | 8.85 | 1 | 0.56 | 0 | 0 | | | | | [105, 181] |
| Zr | Si | 0.160 | 0.696 | | | 735 | 2081 | | 0.353 | | | 8.85 | 1.69 | 8.85 | 1 | 0.69 | 0 | 0 | | | | | [181] |
| Zr | Si | 0.170 | 0.696 | | | 720 | 2095 | | 0.344 | | | 8.85 | 1.81 | 8.85 | 1 | 0.81 | 0 | 0 | | | | | [181, 182] |
| Zr | Si | 0.180 | 0.696 | | | 725 | 2130 | | 0.340 | | | 8.85 | 1.94 | 8.85 | 1 | 0.94 | 0 | 0 | | | | | [105, 181] |
| Zr | Si | 0.190 | 0.696 | | | 724 | 2151 | | 0.336 | | | 8.85 | 2.08 | 8.85 | 1 | 1 | 0.08 | 0 | | | | | [105, 181, 182] |
| Zr | Si | 0.200 | 0.696 | | | 720 | 2172 | | 0.332 | | | 8.85 | 2.21 | 8.85 | 1 | 1 | 0.21 | 0 | | | | | [105, 181, 182] |
| Zr | Si | 0.220 | 0.696 | | | 737 | 2198 | | 0.335 | | | 8.85 | 2.50 | 8.85 | 1 | 1 | 0.5 | 0 | | | | | [105, 181, 182] |
| Zr | Si | 0.230 | 0.696 | | | | | | | | | 8.85 | 2.64 | 8.85 | 1 | 1 | 0.64 | 0 | | | | | [182] |
| Zr | Si | 0.240 | 0.696 | | | 768 | 2297 | | 0.334 | | | 8.85 | 2.79 | 8.85 | 1 | 1 | 0.79 | 0 | | | | | [181] |

**Table A2. Binary bulk metallic glass constitutions, thicknesses, characteristic temperatures and structural parameters.**

| Ω | α | $F_\alpha$ | R | Thickness, mm | $T_g$, K | $T_x$, K | $T_l$, K | $T_{rg}$ | $\Delta T_x$ | $T_x/T_l$ | γ | $\hat{S}_\Omega$ | $\overline{S}_\alpha$ | $\overline{S}_\Omega$ | $S(\alpha_\alpha)$ | $S(\alpha_\beta)$ | $S(\alpha_\gamma)$ | $S(\alpha_\Omega)$ | Citations |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ca | Al | 0.336 | 0.701 | 1 | 528 | 540 | 873 | 0.605 | 0.619 | 12 | 0.385 | 9.00 | 4.37 | 8.63 | 1 | 1 | 2 | 0.37 | [42] |
| Cu | Hf | 0.350 | 1.254 | 2 | 781 | 832 | 1259 | 0.621 | 0.661 | 51 | 0.408 | 16.20 | 7.07 | 13.13 | 1 | 1 | 2 | 3.07 | [65] |
| Cu | Hf | 0.400 | 1.254 | 1 | 773 | 827 | 1290 | 0.599 | 0.641 | 54 | 0.401 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | [64, 66] |
| Cu | Zr | 0.355 | 1.254 | 2 | 747 | 769 | 1243 | 0.601 | 0.618 | 22 | 0.386 | 16.17 | 7.16 | 13.01 | 1 | 1 | 2 | 3.16 | [80] |
| Cu | Zr | 0.360 | 1.254 | 2 | 787 | 833 | 1233 | 0.638 | 0.676 | 46 | 0.412 | 16.15 | 7.25 | 12.89 | 1 | 1 | 2 | 3.25 | [72, 78] |
| Cu | Zr | 0.400 | 1.254 | 1 | 740 | 760 | 1198 | 0.618 | 0.634 | 20 | 0.392 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | [36, 64, 81] |
| Cu | Zr | 0.400 | 1.254 | 1 | 714 | 764 | 1198 | 0.596 | 0.638 | 50 | 0.400 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | [76] |
| Cu | Zr | 0.400 | 1.254 | 1 | 763 | 812 | 1198 | 0.637 | 0.677 | 49 | 0.414 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | [79] |
| Cu | Zr | 0.400 | 1.254 | 1 | 733 | 791 | 1198 | 0.612 | 0.660 | 58 | 0.410 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | [66] |
| Cu | Zr | 0.400 | 1.254 | 1 | 755 | 811 | 1198 | 0.630 | 0.677 | 56 | 0.415 | 15.94 | 7.98 | 11.96 | 1 | 1 | 2 | 3.98 | [78] |
| Hf | Cu | 0.550 | 0.797 | 1.5 | 771 | 830 | 1295 | 0.595 | 0.641 | 59 | 0.402 | 10.77 | 8.12 | 6.65 | 1 | 1 | 2 | 4.12 | [66] |
| Ni | Nb | 0.380 | 1.135 | 2 | 892 | 930 | 1473 | 0.606 | 0.631 | 38 | 0.393 | 14.81 | 7.15 | 11.66 | 1 | 1 | 2 | 3.15 | [56, 134] |
| Ni | Nb | 0.400 | 1.135 | 1 |  | 910 | 1484 |  | 0.613 |  |  | 14.76 | 7.50 | 11.25 | 1 | 1 | 2 | 3.5 | [36, 135] |
| Zr | Cu | 0.450 | 0.797 | 1.5 | 661 | 729 | 1203 | 0.549 | 0.606 | 68 | 0.391 | 10.46 | 6.51 | 7.95 | 1 | 1 | 2 | 2.51 | [75] |
| Zr | Cu | 0.450 | 0.797 | 1.5 | 669 | 719 | 1206 | 0.555 | 0.596 | 50 | 0.383 | 10.46 | 6.51 | 7.95 | 1 | 1 | 2 | 2.51 | [66] |
| Zr | Cu | 0.460 | 0.797 | 2 | 696 | 746 | 1201 | 0.580 | 0.621 | 50 | 0.393 | 10.49 | 6.66 | 7.82 | 1 | 1 | 2 | 2.66 | [135] |